COALMINERS' MORTALITY IN RELATION TO LOW-LEVEL EXPOSURE TO RADON AND THORON DAUGHTERS

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Doctor of Philosophy
University of Edinburgh
1992

DECLARATION

This thesis is submitted in part fulfilment of the requirements for the degree of Doctor of Philosophy. None of the material herein has been submitted for any other degree. Except where due acknowledgement is given, the work is solely that of the author.

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ACKNOWLEDGEMENTS

I should like to thank my supervisor Dr RA Elton of the Department of Public Health Sciences, Edinburgh University, for his guidance and encouragement during the preparation of this thesis. For helpful advice, I also thank Dr RM Agius of the same department; Mr A Bradley, Dr NP Crawford and Mr JF Hurley of the Institute of Occupational Medicine, Edinburgh; Mr D Page, and Dr D Smith of British Coal; and Dr B MacGibbon, Mr J Miles and Mr MC O'Riordan of the National Radiological Protection Board, Chilton. I am grateful too, to Dr M Jacobsen, formerly of the IOM, whose strong advocacy convinced the National Radiological Protection Board that the project was worth supporting.

Most of the figures were prepared by Mr B Turner of the IOM, whose help I gratefully acknowledge. I also thank Miss A McCarron of the IOM, who typed the manuscript with great skill and care. Finally, my thanks are due to Dr CA Soutar and the Board of the IOM for their support and encouragement during the last four years.

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ABSTRACT

Epidemiological studies of many groups of miners, of various ores, have shown that exposure to radon daughters is associated with increased lung cancer risk. These results, together with surveys of indoor radon levels, suggest that indoor exposure might present a hazard for the general population. However, the magnitude of risk at the comparatively low levels found indoors is uncertain, since the exposure of mining groups, on which risk estimates are based, is in general higher. Surveys of radon gas in British coalmines have shown levels of a similar order of magnitude to those indoors, and it therefore appeared that coalminers might be a suitable occupational group in which to study the effects of low-level exposure to radon daughters.

The present study group consists of 19418 male industrial coalmine workers who attended either or both of two medical surveys carried out at 10 British collieries during the 1950s and early 1960s. Deaths in this group up to 31 December 1989 were notified by the Office of Population Censuses and Surveys. Cumulative exposures to radon and thoron daughters acquired during working time were calculated for a subgroup of 14956 men using data from two sources: a set of 146 measurements of daughter levels made at the 10 collieries during the 1970s, and extensive information on time worked underground and on the surface, gathered as part of the British National Coal Board's Pneumoconiosis Field Research. An overlapping subgroup of 14145 men were categorized by smoking habit.

Death rates for two causes – lung cancer and stomach cancer – were tabulated by colliery, calendar time period, age, smoking category, and lagged cumulative exposure to radon or thoron daughters. Relationships between death rates and exposure were investigated by Poisson regression analysis. In a series of matched case-referent studies, relationships between exposure and mortality from these two causes of death, and eight others, were analysed by conditional logistic regression. External comparisons of mortality were made for lung cancer and all-causes only; exposure-response was not examined.

Only men with reliable data on vital status, exposure and smoking were included in statistical analyses – a subgroup of 12361 men. The SMR for all causes was 96, based on 5822 deaths; for lung cancer, 87, based on 521 deaths. Person–years analysis did not show a statistically significant relationship between lagged cumulative exposure to radon daughters and lung cancer death rate. Case–referent analysis showed a joint effect of smoking category and radon daughter exposure upon mortality: relative risks were elevated for non– and light smokers, but were less than unity for heavier smokers. No relationship between thoron daughter exposure and lung cancer mortality was found in either statistical analysis. Neither the person–years analysis, nor the case–referent study, showed any relationship between stomach cancer mortality and exposure. For oesophageal cancer, an apparently negative association between exposure and mortality was observed, which varied with age. No associations were found for any other cause of death examined.

The present study's estimates of lung cancer risk in relation to radon daughter exposure are compared to recently published estimates, derived from studies of uranium and iron–ore miners. Sources of uncertainty in exposures are discussed and the impact of random error upon risk estimates approximately quantified.

Comparisons are made with published work, in which a pattern of interaction between low level radon daughter exposure and smoking similar to that of the present study has been found. The present result may be a combination of a real exposure effect in non– and light smokers, and a bias, perhaps produced by health related job changes. A similar selection mechanism may account for the observed negative association between exposure and oesophageal cancer.

1. INTRODUCTION

1.1 Radon and its Daughters

Radon-222 is an inert radioactive gas formed as part of the decay chain of radium-226. The latter is present, in varying concentrations, in most rocks and soils and thus radon too is found throughout the natural environment (NCRP, 1984). By mechanisms of molecular diffusion, gas flow and water transport - radon is moderately soluble in water - radon can pass to the outside atmosphere, where it is dispersed by convection and turbulence (ICRP, 1987). However, should the gas be transported to mine or indoor atmospheres where ventilation may be limited, higher concentrations can be formed. Access to mines may be directly from the ore, as in the case of uranium mines, or from ground water, as occurred in Newfoundland fluorspar mines (Morrison *et al*, 1984). Access to buildings can be from the subsoil through foundation cracks, or similar defects in the understructure (Nero, 1988), or from building materials themselves, as was found in Swedish houses constructed using lightweight concrete containing alum shale (Swedjemark, 1979). Its chemical inertness and relatively long half-life (3.8 days) ensure that much of the radon evolved within one metre of the soil surface is exhaled to outdoor atmospheres before it decays. If soil is gravelly, or cracked, transport over much greater distances can occur (Nero, 1988).

Radon decays to the radioactive isotope ^{210}Pb through a series of four so-called 'daughter' atoms, which are isotopes of the heavy elements polonium, bismuth and lead. The daughters are all short-lived, and two of them (polonium-218 and polonium-214) emit alpha particles on decay. The diagram, taken from Nero (1988), shows half-lives, and types of emission.

^{222}Rn
↓ (3.82 days, α)

^{218}Po
↓ (3.11 min, α)

^{214}Pb
↓ (26.8 min, β)

^{214}Bi
↓ (19.9 min, β)

^{214}Po
↓ (164 μs, α)

^{210}Pb

When radon decay takes place in air, daughter atoms either become attached to aerosol particles, or remain unattached, existing as ions, molecules or small clusters (NRC, 1991). In either state, they can be inhaled, and deposited in the airways of the lung. The positively charged alpha-particles emitted on decay of ^{218}Po and ^{214}Po have the capacity to damage cells lining the airways, and, in the long-term, cause lung cancer (Samet, 1991). Note that ^{210}Pb itself decays with a half-life of 22.3 years through isotopes of bismuth and polonium to the stable ^{206}Pb. However, its long half-life probably ensures that it is cleared from the lung before decaying (NRC, 1988).

1.2 Radon in Mines

The lung cancer hazard associated with radon daughters has been extensively studied in various groups of miners. The earliest epidemiological evidence came from a study of uranium miners of the Colorado Plateau, begun in 1950 by the US Public Health Service as a result of a request from the Colorado State Health Department and the mining companies. The impetus for the study came from the knowledge that the Colorado mines contained airborne radiation, and that the high prevalence of lung cancer in miners from the Joachimsthal and Schneeberg areas of Czechoslovakia and Germany had been attributed by many investigators to the effects of radiation (Wagoner *et al*, 1964). (Case reports of lung cancers among cobalt miners of the Schneeberg district were given by Harting and Hesse in 1879.) The findings of the Colorado Plateau study appeared in a series of publications. Archer *et al* (1962) reported observed and expected deaths in a group of 2666 white miners between 1950 and 1959 (mortality in 640 non-white miners was not reported). In a subcohort of 907 men with at least three years underground experience, 5 lung cancer deaths occurred compared with 1.1 expected on the

basis of death rates of the general male population of Arizona, Colorado, New Mexico and Utah. A high prevalence of abnormal sputum samples obtained at medical surveys carried out in 1960, together with results of environmental monitoring, which showed that concentrations of daughter products at many of the mines exceeded the recommended working level of 1.3×10^5 MeV of potential alpha energy per litre of air, led the authors to urge that greater efforts should be made to lower exposures. (See Appendix 1 for definitions of units of measurement.) Wagoner *et al* (1964) reported the mortality of 5370 miners and millers, both white and non-white (mainly Indian), over a slightly longer period (1950-62). Fifteen lung cancer deaths were observed, compared to 4.2 expected. In a subcohort of 2500 white underground miners, there were 12 lung cancer deaths compared to 2.8 expected. The mortality of this subcohort was considered in relation to duration of underground mining experience: excess lung cancer was observed only in men with at least five years underground work (11 observed versus 1.1 expected).

Possible reasons for the excess, other than the influence of radon daughter exposure, were discussed by the authors. In particular, they were able to examine whether smoking habit could have contributed, since smoking histories were obtained as part of the study. Their conclusion was that the excess was not due to any of the following: age, smoking, nativity, heredity, urbanization, self-selection, diagnostic accuracy, prior hard rock mining, or other ore constituents including silica dust.

The relationship between lung cancer standardized mortality ratios (SMRs) and cumulative exposures to radon daughters in working level months (WLM - see Appendix 1) was presented by Lundin *et al* (1969) in a report on the mortality of 3414 white and 761 non-white underground miners between 1950 and September 1967. Results for the white subcohort were as follows:

WLM*	Person-years	Lung cancer deaths		SMR
		observed	expected	
<120	10325	8	2.5	3.2
120-359	9554	10	2.4	4.2
360-839	7368	7	2.3	3.1
840-1799	5107	11	1.7	6.5
1800-3719	2406	17	1.0	17.9
⩾3720	679	9	0.2	37.5
All	35439	62	10.1	6.2

*Estimated to time at risk or 1963, whichever was earlier.

The authors judged that differences in smoking habits could not explain the marked exposure–response relationship: cumulative exposure to cigarettes was similar in exposure groups, allowing for age. Estimation of exposures was described briefly by Wagoner *et al* (1965). They were based on approximately 12,000 measurements of radon daughter level made for control purposes, and estimates of daughter levels which were made at most of the 1200 mines involved, for at least some years of the follow–up. Occupational histories were obtained from miners at the triennial medical examinations held as part of the study.

Mortality from 87 cause groups up to 31st December 1977 in 3362 white underground miners was reported by Waxweiler *et al* (1981). There were 950 deaths observed compared with 600.3 expected on the basis of US National rates. Notable excesses were from lung cancer (185 versus 38.4), non–malignant respiratory disease (103 versus 31.6), chronic and unspecified nephritis and renal sclerosis (8 versus 3.1) and accidents (155 versus 46.8). Variations in SMRs with cumulative exposure to radon daughters were not examined in this paper. More recent reports on the mortality of the Colorado miners (Whittemore and MacMillan, 1983; Hornung and Meinhardt, 1987) have used proportional hazards models (Cox, 1972) to examine the joint influence of smoking and exposure (considered below), and the effects of time–dependent factors such as age at first exposure and years since cessation of exposure.

First results from a follow-up of Czechoslovak uranium miners were reported in 1971 by Sevc *et al*. An analysis of excess lung cancer rates in a group of 2433 miners followed up from 1948 to 1975 was presented by Kunz *et al* in 1979. As in the American study, excess mortality was found to increase with cumulative exposure (WLM). However, the increasing trend was manifest over the entire cumulative exposure range only for exposure periods longer than 12 years. For shorter periods of exposure, the exposure response curve fell away at higher cumulative exposures. Results in this paper were expressed as additional lung cancer cases per 1000 miners, instead of the more conventional 'per 1000 person-years', which made comparison with other studies difficult. Results presented by Kunz *et al* (1978), pertaining to a follow-up period 1948 to 1973, gave observed and expected deaths by exposure category per 10000 person-years, and numbers of person-years at risk. They are reproduced below:

		Lung cancer deaths per 10000 person-years		
WLM	Person-years	observed	expected*	SMR
<100	9380	6.4	5.5	1.2
100-199	16131	24.8	7.6	3.3
200-399	19614	42.8	7.7	5.6
≥400	11830	69.3	8.4	8.2
All	56955	37.2	7.5	5.0

* Obtained from Czechoslovak national rates.

Sevc *et al* (1976) reported that the prevalence of cigarette smoking in a random sample of 700 miners was equal to that of the general male population of Czechoslovakia.

Two large-scale Canadian studies of uranium miners have been reported. Muller *et al* (1985) examined the mortality of Ontario miners in general, considering miners of several different types of ore, including uranium.

Excess lung cancer mortality was found in 7542 gold miners and 15948 uranium miners, over a 13-year follow-up, from 1/1/55 to 31/12/77. Two sets of exposures to radon daughters (WLM) were calculated for the uranium miners, and it was considered that these provided upper and lower bounds for men's true exposures. Four exposure-response curves were presented, which used lower and upper exposures for each of two groups of uranium miners - those with and without prior gold mining experience. Results for the latter group (lower WLM) are given below. (Possible differences in smoking habit between the miners and the general population were not examined.)

			Lung cancer deaths		
WLM	Mean WLM	Person-years	observed	expected*	SMR†
0.1-6	3	51356	14	11.7	1.2
6.1-20	12	61823	13	17.2	0.8
20.1-40	29	38751	15	11.0	1.4
40.1-70	53	23313	13	7.0	1.8
70.1-140	98	17345	12	6.0	2.0
>140	200	10208	15	4.1	3.6

* Based on the male population of Ontario.

† Calculated from the observed and expected figures given by Muller *et al* (1985).

In the second Canadian study, mortality during 1950-80 in a cohort of 8487 uranium miners employed by Eldorado Resources Ltd at the Beaverlodge uranium mine in Saskatchewan was reported by Howe *et al* (1986). In a detailed analysis, the authors considered the relationship between lung cancer risk and cumulative exposure (WLM), and also how this might be modified by time-related factors, in particular years since first exposure, age at first exposure and age at risk. Exposures acquired later than 1967 were based on radon daughter concentration measurements, which were made several times each month in occupied mine areas. Earlier exposures were derived from sparser control measurements. Smoking data were not available for the cohort; the authors considered that the SMR of 1.0 in the lowest exposure

category (see Table below) provided evidence that the miners' smoking habits did not differ from those of the general population.

WLM	Mean WLM	Person-years	Lung cancer deaths observed	Lung cancer deaths expected*	SMR
0-4	0.9	29818	14	14.5	1.0
5-24	11.7	14815	12	6.5	1.8
25-49	35.6	5554	5	2.6	1.9
50-99	69.8	3755	6	2.5	2.4
100-149	121.1	1607	7	1.2	6.0
150-249	187.4	1051	6	0.8	7.9
≥250	294.9	342	4	0.3	14.2
All	20.2	56942	54	28.3	1.9

* Based on Canadian rates.

The lung cancer hazard associated with radon daughters is not confined to uranium mines; increased risks have now been demonstrated in other mining groups, for example, Swedish iron miners, Canadian fluorspar miners and Chinese tin miners. Radford and St Clair Renard (1984) studied mortality over the period 1951-76 in 1415 Swedish iron-ore miners. Using death rates for Swedish males, they calculated an expected figure of 12.8 lung cancer deaths, compared to 50 observed. Cumulative exposures were calculated from radon daughter measurements made in 1968 and later years, and from levels estimated for earlier years from knowledge of ventilation conditions. Smoking habit was taken account of in analyses (see Section 1.6 below). The overall exposure response relationship was as follows:

WLM	Mean WLM	Person-years	Lung cancer deaths observed	Lung cancer deaths expected*	SMR
0-49	26.8	8981	8	3.4	2.4
50-99	73.0	7025	14	3.6	3.9
100-149	123.0	4483	4	2.5	1.6
150-199	171.9	2805	18	2.4	7.4
≥200	217.7	789	6	1.0	6.3
All	81.4	24083	50	12.8	3.9

* Swedish national rates.

The mortality experience of 1772 Newfoundland underground fluorspar (calcium fluoride) miners during 1950–1984 was reported by Morrison *et al* (1988). High lung cancer rates among miners, pointing to a possible occupational hazard, were noticed in the 1950s; the first radon measurements were made in 1960 and showed levels as high as 190 WL. Levels fell markedly upon the introduction of mechanical ventilation in 1960. Exposures in the study group were derived from radon daughter measurements made in 1960 and later years (from 1969, daily exposures for each worker were recorded), and from levels estimated by the Atomic Energy Control Board for the pre–1960 period. Cigarette smoking information was obtained for 48% of the cohort, at three surveys. Over the 25–year study period, 113 lung cancer deaths were observed, compared with 21.5 expected on the basis of Newfoundland rates. A strong exposure–response relationship was evident:

WLM	Mean WLM	Person-years	Lung cancer deaths observed	Lung cancer deaths expected*	SMR
0	0.0	9051	6	6.7	0.9
<50	10.3	11261	13	7.2	1.8
<100	77.1	2454	3	1.9	1.6
<400	229.4	6980	12	5.6	2.1
<1000	607.3	4281	14	3.2	4.4
<1600	1284.2	1734	14	1.2	11.3
<2500	1964.8	1579	25	1.0	24.0
≥2500	3449.1	1170	29	0.9	33.6

* Newfoundland rates.

Results of a case–control study among employees of the Yunnan Tin Corporation (YTC), Yunnan Province, China, were reported by Qiao *et al* (1989). Cases of lung cancer in males aged 35–80 which were reported to the Labor Protection Institute of the YTC during 1967–84, and who survived to 1985, formed the case series. Each of the 107 cases was matched to a single control on year of birth (5–year bands) drawn from a list of past or present employees of the YTC. Occupational and smoking histories were obtained by questionnaire. WL values for individual tin mines for the post–1973 period were based on measurements made for monitoring purposes; for 1953–72, on 413 radon daughter samples specially obtained in 1972 for the purpose of back estimation; and for the pre–1953 period, from 117 measurements made at 13 small mines which had operated before large–scale operations started in 1953. Ratios of the odds of developing lung cancer between radon daughter exposure categories and a non–exposed category, adjusted for age, arsenic exposure, date of starting work at YTC, and smoking, were as follows:

WLM	Odds ratio (95% confidence limits)
0	-
1-240	4.8 (1.6, 14.8)
241-541	15.0 (4.4, 50.8)
542-1762	9.5 (2.7, 33.1)

Two studies of miners' mortality in Britain have shown or suggested links between radon daughter exposure and lung cancer. Causes of death were ascertained by Boyd *et al* (1970) for all men over 15 years of age who had lived in an iron-mining area of West Cumberland (5811 men) and who had died during 1948-67. Men were classed as iron miners, coal miners, or as working in other occupations; causes of death considered were lung cancer, other cancer, respiratory causes, and other causes. The observed number of lung cancer deaths in the iron miners was compared with an expected number, calculated from the ratio of numbers of lung cancer deaths to 'other causes', in the 'other occupations' group. The calculation was carried out within age and district subgroups. Results were: observed deaths = 42, expected = 27.7, for the iron miners as a whole. The excess was in fact confined to underground workers (obs = 36, exp = 20.6). Results using proportionate mortalities for England and Wales instead of for 'other occupations' were very similar. The authors suggested that the increased risk might be due to radioactivity in the mine air, or to a carcinogenic effect of iron oxide.

Hodgson and Jones (1990) analysed the mortality of a cohort of Cornish tin miners from 1941 to 1986. The study group consisted of 3082 men with at least one year's mining experience at one of two tin mines between 1/1/41 and 1/5/84, for whom an occupational history could be obtained from work records. Men over 60 at the start of their mining work were excluded, as were men born before 1880. Individual exposures (WLM) were not estimated; measurements made since 1969 suggested that the average underground exposure would be approximately 10 WLM annually. One hundred and five lung cancer deaths were observed compared with 66.6 expected using rates for England and Wales. A test for trend in the SMR with time underground was statistically significant, the SMR reaching 4.5 at > 30 years underground work. The influence of duration of exposure, time since first exposure and date of first exposure were examined by regression methods. An effective dose, given by the time integral of an assumed 'pattern of effect' following one year's exposure, was found to relate to lung cancer mortality more strongly than time underground. The authors concluded that the results provided evidence of a clear relation between radon

exposure and lung cancer. Smoking information was not available; the fact that mortality from ischaemic heart disease was not exceptional suggested that cigarette consumption would not have been unusually high.

To summarise, studies of miners of various ores have shown conclusively that radon daughter exposure presents a lung cancer hazard. Explanation of the observed associations in terms of confounding by smoking is unlikely; investigation of this possibility for the cohorts of uranium miners from the Colorado Plateau and Czechoslovakia, for Swedish iron miners, and for Chinese tin miners showed that such confounding could not account for observed trends. As might be expected, there is some disagreement as to the magnitude of the exposure–response gradient. A simple linear regression (weighted by expected deaths) of the form

$$SMR = 1 + \beta(WLM)$$

carried out for the data reported here, gave a range of coefficients from 0.0062 for the Colorado Plateau cohort to 0.0376 for the Beaverlodge (Saskatchewan) cohort. Because of the relatively small numbers of deaths occurring in the lower WLM categories, it is unclear whether these coefficients would continue to apply at low levels of radon daughter exposure, such as those found indoors.

1.3 Indoor Radon

The presence of radon at concentrations which could be judged to be potentially hazardous in the indoor air of some Swedish homes was reported by Swedjemark (1979). The highest levels were found in houses built of aerated concrete containing alum shale; a group of nine such dwellings, with natural ventilation, had a mean radon daughter concentration of 410 Bq m^{-3}. Thirty years exposure at this concentration, assuming an occupancy of 80%, would give a cumulative exposure of 137 WLM – sufficiently great to cause excess lung cancer mortality, according to epidemiological studies of Colorado and Czechoslovak uranium miners (see Section 1.2).

Nero (1988) summarized the results of surveys of indoor radon levels in North America, Japan and several European countries. Average concentrations ranged from 25 Bq m^{-3} in the UK to 122 Bq m^{-3} in Sweden. Two percent of detached houses in a Swedish sample of 500 apartments and detached houses, had levels of radon in excess of 800 Bq m^{-3}. In the UK, a survey of 2093 homes undertaken by the National Radiological Protection Board, showed an average concentration of 20.5 Bq m^{-3}, adjusted for differences between the national housing stock and the sample (Wrixon *et al*, 1988). There were wide regional variations: 11 homes in Central Region Scotland had a mean level of 10.2 Bq m^{-3}, 16 in Cornwall and the Isles of Scilly had a mean level of 114.3 Bq m^{-3}. Special regional surveys showed mean levels of 300 Bq m^{-3} in selected areas of South-West England. These results led NRPB to recommend that action be taken to reduce radon concentrations in buildings where persons would be exposed to 400 Bq m^{-3} or more (NRPB, 1987).

The growing awareness that indoor radon might present a lung cancer hazard, prompted a series of epidemiological studies, mainly of the case-referent type, and mostly carried out in Sweden. Axelson *et al* (1979) compared the types of dwellings which had been occupied by 37 lung cancer cases who had died in 1965-77, to those of 178 referents, who had died of non-cancer causes. The study was carried out in a rural area of southern Sweden, a rural area being preferred on the grounds that the population would be less mobile, and that a wider range of housing types would be represented. Subjects' past dwellings were grouped as follows: (0) wooden houses, without basements, (1) dwellings other than those grouped under (0) or (2), (2) stone houses, with basements. The authors referred to results of surveys carried out by Hultqvist (1956) to support the notion that wooden building materials would produce less radon than other types of material. Allowing for age and sex differences by stratification, the estimated relative risk of lung cancer between groups (1) and (2) combined, compared to (0), was 1.8 (90% confidence limits, 1.0-3.2). Smoking habit was available only for a few of the subjects.

A similar classification of dwellings was used by Edling *et al* (1984) in a case-referent study carried out in the Baltic Island of Oeland. The presence of a narrow strip of alum shale in the south-west of the island made it likely

that some dwellings in this area would have high levels of radon. Twenty-three cases of lung cancer were identified, who had died during 1960-78 aged 39 or over, and who had lived in the same house for at least 30 years prior to death. Two hundred and two referents who had died from non-cancer causes, were the comparison group. The classification of dwellings, made by visual inspection, was as follows: (0) wooden houses, without a basement, on 'normal ground' (i.e. not on alum shale); (1) dwellings other than those grouped under (0) or (2); (2) wooden houses, with a basement, on alum shale, or stone, brick or plaster houses, with a basement, on any ground, or stone, brick or plaster houses, without a basement, on alum shale. Smoking information was obtained by questionnaires to next-of-kin, and radon daughter concentrations were measured in 86% of the subjects' houses. Logistic regression analysis gave a relative risk of lung cancer for groups (1) and (2) combined, versus group (0), of 3.9 (90% confidence limits 1.5-10.0), allowing for age, sex and smoking habit. In an analysis of exposure levels (Bq m^{-3}), the relative risk for exposure group 50 Bq m^{-3} or more, versus less than 50 Bq m^{-3}, was 4.7 (90% confidence limits 1.2-18.5).

Svensson *et al* (1987) attempted to estimate cumulative exposures to radon daughters for 292 female lung cancer cases belonging to the 'unspecified epithelial group', diagnosed in Stockholm during 1972-80, and for 584 referents, matched on year of birth. Addresses were classified as 'radon +' or 'radon -'. The relative risk for 'radon +' versus 'radon -' was 2.2 (95% confidence limit 1.2-4.0), but an analysis of cumulative exposure (Bq m^{-3} year) did not show a statistically significant difference in risk (P = 0.29). Smoking habit was not allowed for.

In 1979 a large case-control study was begun in northern Sweden, primarily aimed at investigating links between occupation and lung cancer risk. Interest in radon exposure prompted the inclusion of an item on building materials in the study questionnare; an analysis of mortality by a surrogate variable for cumulative exposure to radon daughters, namely years in non-wooden houses, was subsequently reported by Damber and Larsson (1987). In the analysis, 589 male lung cancer cases occurring in the three most northern counties of Sweden during 1972-77 were compared to 1035

matched controls, 582 of whom were deceased. Information on type of dwelling, occupation, employment and smoking had been gained by questionnaire, administered either to relatives, or to living controls. Differences in mortality rates between three exposure categories (<1 year, 1–20 years, >20 years) were not statistically significant, allowing for smoking habit, although relative risks did increase with increasing exposure.

Axelson *et al* (1988) designed a case–referent study intended to reproduce the results of Edling *et al* (1984). Cases were deaths from lung cancer, taken from the National Register, and occurring during 1960–81 in a defined area in Central Sweden, with known deposits of alum shale. Referents were non–cancer deaths, also from the Register. Exclusions of subjects, for various reasons, reduced the number of cases from 1087 to 177, and the number of referents from 4348 to 673. Subjects' dwellings were categorized as in Edling *et al* (1984); radon daughter measurements were made in as many of the cases' houses as possible (142) and in a sample of referents' (264), and smoking information was obtained from next–of–kin. A statistically significant trend across exposure categories coded 0, 1 and 2 (see description of Edling *et al*, 1984, above) was observed, allowing for the effects of age and sex, but not for smoking. Estimated risks, relative to category 0, were 1.4 and 1.7 for categories 1 and 2, respectively. An interaction between smoking habit and exposure category was also found, and is discussed below.

Finally, in this series of Swedish studies, Svensson *et al* (1989) demonstrated statistically significant differences in lung cancer risk between categories of cumulative exposure to indoor radon, and an increasing trend in risk for small cell cancer in particular, in a case–control study in Stockholm County. Cases were 210 incident female cases, over an unspecified period; controls (two series) had either been admitted to hospital on suspicion of lung cancer, later discounted (191 patients), or were drawn from the general population of Stockholm (290 subjects). Occupational and residential histories, and also smoking information, were obtained from study subjects at interview. Cumulative exposures were assessed using information on dwelling type, ground characteristics and building material, together with radon measurements made in a stratified sample of subjects' houses. Analyses were restricted to 524

subjects with information on type of dwelling. The relative risks of lung cancer, adjusted for age, smoking and municipality, were:

Exposure (Bq m^{-3} years)	Relative risk (95% confidence limits
-4500	1
4501-6000	1.8 (1.2-2.9)
6001-	1.7 (0.9-3.3)

Risks of small cell cancer were more strongly related to exposure:-

Bq m^{-3} years	Relative risk (95% confidence limits)
-4500	1
4501-6000	1.9 (0.6-4.5)
6001-	4.7 (1.5-14.2)

Several studies of indoor exposure have also been carried out in North America. Simpson and Comstock (1983) studied lung cancer rates during 1963–75 in a group of white residents of Washington County, Maryland, aged over 25 in 1963. Study subjects were those who had been enumerated in a census of 1963, and who had provided information on personal and housing characteristics. Incident cases of lung cancer were identified in the County Cancer Registry; incidence rates were calculated using an estimate of the 1969 county population. Using multiple regression, age, smoking, sex and socio–economic status were found to be associated with incidence rates. Differences in incidence between 4 categories of construction type, 6 categories of building material, 4 categories of heating, and 3 categories of cooking fuel, were not statistically significant.

As a result of public concern over radioactivity levels, a complete survey of radon levels in the town of Port Hope, Ontario, was undertaken in 1975 (Lees *et al*, 1987). In 1953, a factory which had produced uranium and radium had been demolished, and much of the rubble and other building material had been re–used for construction purposes throughout the town. The possibility that the resulting radioactive contamination might be causing adverse health effects was examined in a case–control study of lung cancer begun in 1980. Cases were persons who developed, or died from, lung cancer during 1969–79, and who had lived in Port Hope for at least seven

years prior to diagnosis. The main source was the registry maintained by the Ontario Cancer Treatment and Research Foundation. Controls were patients on the Registry with other cancers, or, if selected from Port Hope physicians' files, with a non-cancer diagnosis. Two controls were chosen for each case, matched by date of birth and sex. Controls were also required to have lived in Port Hope for at least seven years, and their period of residence had to overlap by at least a year, the seven-year period prior to the diagnosis of the case. Interviews with subjects or next-of-kin yielded occupational and residential histories, and also smoking information. Estimated cumulative exposures to radon daughters were based on survey data, together with residential histories; 0.229 WLM per annum was subtracted as background. After exclusions, mostly of subjects who had worked at the local processing plant, 27 cases and 46 controls remained for analysis. All controls, and 77% of cases had exposures less than 4 WLM. Conditional logistic regression analysis, allowing for smoking, gave an odds ratio of 2.36 (95% confidence limits 0.786-7.11) for exposed persons (> 0 WLM) versus non-exposed (0 WLM). Analysis of a different characterization of exposure, according to whether the subject's home was above or below background, gave a higher estimate of relative risk - 6.81 (0.513, 90.6). Finally, an analysis in which exposure was treated as a continuous variable on the log scale, showed a significant increasing trend in risk (P = 0.014). Estimated odds ratios were:

Exposure (WLM)	Odds ratio
1	1.05
5	6.36
10	11.89

The authors stressed that the results be interpreted with caution, in view of the small numbers, and uncertainty concerning exposures.

Community concerns also prompted a historical cohort study of the mortality of persons who had lived in certain dwellings in Essex County, New Jersey, identified in surveys as having high levels of radon daughters (Klotz *et al*, 1989). These houses (45 in number) had been built on soil contaminated by waste from demolished factories, which had used or processed radioactive

material. Study subjects were persons who had lived in any of the 45 houses for at least a year, until 1983. Tracing was accomplished by a variety of means, including City Directories, school records, voting rolls and others; vital status was established from lists of deceased persons available for the three towns involved in the study. Cumulative exposures in WLM were estimated from radioactivity survey data combined with residential history. Comparison of observed deaths among the 752 study subjects with those expected under US rates 1925–83, showed excess rectal cancer (SMR = 3.36), and slight excess lung cancer (SMR = 1.23). There was no evidence of trends in SMRs with increasing exposure.

The most recently reported North American study of lung cancer in relation to radon exposure (Schoenberg *et al*, 1990) arose out of a more general case–control study of lung cancer, smoking, diet and occupation conducted among New Jersey women during 1982–84. Cases were female lung cancer cases, resident in New Jersey, and newly diagnosed in 1982/83. Controls for living cases were randomly chosen from New Jersey driver's licence files (ages less than 65) or from Health Care Financing Administration files (ages 65 or more), and were frequency matched for age and race. Controls for deceased cases were selected from death certificates with no mention of respiratory disease, and were individually matched on race, age and closest date of death. As part of the more general case–control study, smoking and occupational histories had been obtained at interview of study subjects or next of kin; for the radon study, follow–up interviews were conducted to determine detailed residential histories. Subjects were only included in analysis if they had lived at a single residence (the 'index' residence) for at least 10 years in the period between 10 and 30 years prior to diagnosis or selection as a control. Cumulative exposures were calculated from year–long measurements of radon levels in index residences, together with residential histories. For years lived in dwellings other than index residence, the median index residence radon level for controls was used. Statistical analyses were based on 433 cases and 402 controls; relative risks estimated by multiple logistic regression analysis, were adjusted for smoking, age, occupation (high risk for lung cancer, or low risk) and respondent type (subject or next–of–kin). Relative risks by radon concentrations in index residences showing an increasing trend (P = 0.04):–

Radon level (pCi/litre*)	Relative risk
<1	1
1-1.9	1.1
2-3.9	1.3
4-11.3	4.2

(* 1 pCi/litre = 37 Bq/m^3)

A trend with cumulative exposure was also apparent, but weaker (P = 0.09).

A case–control study of lung cancer in relation to indoor radon was carried out by Blot *et al* (1990) in the Chinese city of Shenyang, where lung cancer rates among women are exceptionally high. Cases were females aged 30–69, diagnosed during 1985–87; controls were sampled from the general population, and were frequency matched to cases, by age. The information sought at interview comprised residential, occupational and smoking history; only five percent of patients could not be interviewed. Radon levels were measured in the current residences of cases and controls, over a period of one year. For some subjects who had lived at their current address for less than five years, radon measurements were made at their previous residence. After exclusions for missing data, 308 cases (79% of those eligible) and 356 controls (91%) were included in analysis. Logistic regression analysis, with adjustment for age, education, smoking and an index of indoor air pollution, did not show evidence of an increasing trend in risk with home radon level.

Finland, in common with Norway and Sweden, has high levels of indoor radon (ICRP, 1987). Ruosteenoja (1991) carried out a correlation study (summarized below) and a case–control study in southern Finland, to investigate whether exposure levels were related to lung cancer risk. Three hundred and eighteen male incident cases of lung cancer during 1980–85 in 19 municipalities of southern Finland were identified from cancer registry and hospital records. For various reasons, described in the report, 27 men were excluded. Potential controls (1500) were a random sample, stratified by age, of all men living in the study municipalities on 1st January 1980. Questionnaires requesting smoking data were sent to potential controls; the resulting information enabled the selection of a control group (495 men)

as age. Interviews, residential, occupational and smoking histories. Addresses o. upied for longer than one year since 1950 were obtained. The r for Radiation and Nuclear Safety attempted to make measurements ch dwellings, but for a variety of reasons, obtained data for only 6. ge radon concentrations were calculated for each subject for the period . 75; in logistic regression analysis subjects were weighted according to the pro ortion of this 25-year period they had lived in 'measured' residences. Estimated risks relative to a base category of < 109 Bq m^{-3}, adjusted for smoking, year of birth, education (primary or higher) and occupation, were obtained for a group of 164 cases and 334 controls. Differences between exposure categories were statistically significant, but there was no significant trend:

Measured indoor radon level (Bq m^{-3})	Odds ratio (95% limits)
<109	1.00
109-150	1.12 (0.56-2.21)
151-196	1.73 (0.87-3.44)
197-264	1.85 (0.96-3.58)
≥265	1.13 (0.57-2.22)

Summing up, it seems reasonable to say that epidemiological studies of indoor exposure have yet to provide strong evidence of a lung cancer hazard. Of the 12 studies reviewed above, four were negative, and one (Ruosteenoja, 1991) while showing differences between exposure categories, did not establish a trend. In some of the positive studies, the fact that a surrogate variable for exposure was used (perhaps type of dwelling, or years in non-wooden house), weakened the conclusion that radon exposure might be the responsible agent; in others, smoking habit was not allowed for.

1.4 Radon Exposure and Mortality from Causes other than Lung Cancer

Several studies of miners have shown excess mortality, compared to national or regional rates, from causes other than lung cancer. For the Colorado Plateau cohort, Wagoner *et al* (1964, 1965) reported higher than expected death rates for a remainder group of 'all other causes', which were largely

due to an excess of deaths from pulmonary fibrosis and its complications. Lundin *et al* (1969), in a follow-up of 3414 white miners, found 12 deaths from respiratory tuberculosis over an 18-year period compared to 3.4 expected, in a subgroup of men with at least 10 years prior hard rock mining experience. Waxweiler *et al* (1981) studied mortality from 87 causes in essentially the same cohort over the same period. Using US rates for comparison, excess mortality was found for 'other non-malignant respiratory disease' (mainly silicosis, emphysema and fibrosis - 83 observed, 16.6 expected), chronic nephritis and renal sclerosis (8 observed, 3.1 expected), and tuberculosis (14 observed, 3.4 expected). The death rate from accidents was also raised (155 observed, 46.8 expected). The relationship between SMRs and time elapsed since beginning uranium mining was examined for various causes; SMRs for chronic nephritis and non-malignant respiratory disease both tended to increase with increasing time elapsed. In discussion, the authors pointed out that five of the nephritis cases had had previous exposure to other nephrotoxins (lead, gold and cadmium), and suggested that links between kidney disease and mining were probably not specific to the uranium mining industry.

A group of 15984 Ontario uranium miners studied by Muller *et al* (1985) experienced increased death rates from silicosis and chronic interstitial pneumonia (11 observed, 2.1 expected) and accidents, poisoning and violence (497 observed, 222.8 expected). However, only lung cancer SMRs were considered in relation to cumulative radon daughter exposure. Howe *et al* (1986), in a study of 8487 Saskatchewan uranium miners reported no significant excesses for non-cancer causes, other than accidents and suicides. In higher exposure categories ($\geqslant$50 WLM), the only notable excess of cancer (other than of the lung) was one death from salivary gland cancer compared to 0.01 expected.

In their study of Swedish iron miners, Redford and St Clair Renard (1984) found that the excess in cancer mortality was entirely due to lung cancer and stomach cancer, observed and expected deaths from the latter being 28 and 15.1 respectively. Seven deaths from lymphoma were observed, compared to 4.7 expected, a non-significant excess. Non-cancer mortality was not tabulated by cause, but significant excesses from cardiovascular disease,

silicosis, and occupational accidents were mentioned. Exposure response was considered only for lung cancer mortality.

Morrison *et al* (1988) reported excess mortality from cancer of the buccal cavity and pharynx (6 observed, 2.2 expected) and of the salivary gland (2 observed, 0.1 expected), in a cohort of Newfoundland fluorspar miners. Small numbers prevented exposure–response analysis, but it was noted that cases of buccal cavity and pharyngeal cancer tended to have lower exposures. A non–significant excess was observed for stomach cancer; there was no excess of cancer of the digestive tract. Possible trends in SMRs with exposure were investigated for both these cancers, but were not statistically significant.

Elevated rates of stomach cancer (27 observed, 19.1 expected) and leukaemia (7 observed, 4.0 expected) reported by Hodgson and Jones in their study of Cornish tin miners (1990) were not statistically significant; trends with time worked underground were also non–significant. However, observed deaths from both silicotuberculosis and silicosis, expressed as percentages of total expected deaths did show evidence of an increasing trend. In common with many other mining groups, mortality from accidents, poisoning and violence was raised (51 observed, 36.3 expected).

Studies of indoor exposure, being mainly of the case–referent design, have focussed on lung cancer. Klotz *et al* (1990), in their historical cohort study of mortality in a residential cohort in New Jersey, reported excess rectal cancer, heart disease and cerebrovascular disease. However, analysis of high exposure subgroups showed no indication of exposure–response.

Although many of the cohort studies of miners have shown excess mortality from causes other than lung cancer, there is to date no convincing evidence that exposure to radon and its daughters has contributed to these excesses.

1.5 Correlation Studies

The relationship between incidence or mortality rates for cancers at various sites and indoor exposure to radon, has been investigated by several groups of workers, using the so-called correlation or descriptive approach. By this method, age standardized rates for defined geographical regions are correlated with estimates of average indoor radon levels for the regions. The advantage of the approach is that hypotheses can be explored quickly and cheaply using existing data. Foremost among the disadvantages is the inability to adjust correlations for the effects of potential confounding variables such as smoking and air pollution.

Edling *et al* (1982) compared county death rates in Sweden (for varying periods during the 1960s and 70s) for five causes of death - leukaemia, multiple myeloma, and cancer of the lung, pancreas, and female breast - with estimates of the average background gamma radiation for the counties, reported by the Swedish Institute for Radiation Protection. The authors considered that background gamma radiation and indoor radon levels would be well correlated. Significant positive correlations ($P < 0.05$) were found for lung cancer (males and females), leukaemia (males) and pancreatic cancer (males and females).

Correlations between cancer incidence rates for the years 1969-71, 1973-78 for 28 towns in Iowa USA and levels of radium-226 in public water supplies were examined by Bean *et al* (1986b). (Radon is moderately soluble in water, and can be released to the indoor atmosphere by agitation or heating. The reason for the omission of 1972 rates is not given explicitly, but would appear to be lack of data. In a companion paper (Bean *et al*, 1982a), the authors write that the state of Iowa was part of the Third National Cancer Survey of 1969-71, and in 1973 joined the National Cancer Institute Surveillance, Epidemiology, and End Results Program.) Age-adjusted lung cancer incidence rates were found to be positively related to radium-226 water content, but the trend was significant only for males. Multiple regression analyses of standardized incidence ratios for lung cancer, using Iowa rates as standard, showed a significant relationship (again, for males only) with radium-226 content, allowing for income, percentage of manufacturing workers,

percentage of rural workers and water fluoride level. Smoking was not allowed for in analyses, but results from a national study of bladder cancer cited by the authors suggested that the percentage of smokers in towns of high water radium content, was lower than the percentage of smokers in towns of low water radium content.

A similar study was carried out by Hess *et al* (1983). County average levels of radon in water from public and private wells in 16 counties of Maine, USA were compared with age-adjusted deaths rates (1950-69) for several cancers. Increasing trends in lung cancer rates with increasing radon levels were observed for both males and females, but were statistically significant ($P < 0.05$) only for females.

High rates of stomach cancer mortality in the north and north-east of the state of New Mexico (USA) coincide geographically with areas of commercially viable uranium deposits. Associations between age-adjusted death rates (1970-79) from stomach cancer among whites in the 32 counties of New Mexico, and the presence of significant uranium deposits, were investigated by Wilkinson (1985). Allowing for sex and ethnicity (Hispanic versus Anglo), the proportion of counties with uranium deposits whose stomach cancer death rates exceeded the New Mexico rate, was significantly higher than the corresponding proportion of those counties without uranium deposits. The author suggested that residents of counties where there were high uranium deposits might be exposed to higher levels of environmental radionuclides such as radon and radon daughters. He pointed to a study of uranium miners (Waxweiler *et al*, 1981) which had shown a non-significant excess of stomach cancer.

In a recent review of radon and lung cancer, Samet (1989) refers to an incident which occurred in 1984 at a Pennsylvania nuclear power plant. A worker at the plant was found to be contaminated by radioactivity, the source of which was eventually identified as indoor radon. The worker's home was situated on a granite formation known as the Reading Prong, which runs south-west from New York State to Reading, Pennsylvania. High levels of radon have been measured in many homes located on this geological feature (Samet, 1989, citing Logue and Fox, 1985). Archer (1987) calculated

age-adjusted lung cancer death rates (1950-79) for 33 counties in the vicinity of the Reading Prong. Counties were split into three groups - those where granites were found in at least one quarter of the county (the Reading Prong group), a 'fringe' group bordering the Reading Prong counties but with less granite, and a 'control' group lying mostly to the north and west of the Reading Prong. Rates showed a significant trend across the three groups ($P < 0.01$). Several potential confounding variables were considered: socioeconomic status, measured by average income, increased from the control group to the Reading Prong group; the degree of urbanization of the three groups was roughly equal; analysis by sex showed the same trend for males and females separately. However, there was no information on average smoking habits in the counties.

As part of an investigation into radiation dose from inhaled radon to organs other than the lung, Henshaw *et al* (1990) calculated the correlation coefficient between age standardized national incidence rates of myeloid leukaemia (chronic and acute) and average indoor radon levels for 14 countries. The result (0.65) was statistically significant at the 2% level. The same calculation using regional data, gave a coefficient of 0.62 ($P < 0.01$). Regional incidence rates of acute myeloid leukaemia in Canada had a particularly high correlation with indoor radon levels (0.86, $P < 0.01$); and rates of kidney cancer for the same regions also showed a high correlation (0.86, $P < 0.01$). The authors also examined melanoma rates: the correlation for regional and national data combined was 0.81 ($P < 0.001$). Lung cancer rates however did not show a correlation with radon levels, a fact which the authors attributed to the dominating effect of smoking in general populations. Following publication of a study which suggested the possibility of a link between childhood cancer incidence and the occupation of the father (Gardner *et al*, 1990), Eatough and Henshaw (1990) reported correlations between incidence rates of cancers of the reproductive organs and average indoor radon levels for the same 14 countries considered previously. The coefficient for prostate cancer (0.72) was statistically significant ($P < 0.01$). Butland *et al* (1990) subsequently commented on these results. They pointed out that cancer registration data from some of the 14 countries considered by Henshaw *et al* were incomplete. In a re-analysis, excluding

countries with less reliable data, correlations for myeloid leukaemia, kidney cancer and melanoma were no longer statistically significant.

Finally, in this series of correlation studies, Ruosteenoja (1991) compared standardized lung cancer incidence rates in males (1973–82) in 18 municipalities in south Finland, with average radon levels based on measurements provided by the Finnish Centre for Radiation and Nuclear Safety. This study was carried out in combination with a case–control study, summarized above, the results of which allowed estimation of the prevalence of smoking in study municipalities. The correlation coefficient between incidence rates and radon levels was 0.36 ($P = 0.14$); adjustment for smoking did not alter the result. The author drew attention to the non–randomness of the radon survey. If 'problem houses' were more likely to be surveyed, an over–estimation of municipality averages would have occurred, possibly leading to underestimation of the correlation.

The evidence from correlation studies must be regarded as considerably weaker than that from studies of individual subjects. As well as the problem of confounding variables mentioned above, there is the difficulty of ensuring compatibility between regions defined for the purpose of computing rates, and regions to which average exposures are presumed to apply. Furthermore, migration between regions may bias comparisons of rates – for example, persons moving from 'high risk' to 'low risk' regions would carry their enhanced risk with them. Such studies cannot be expected to provide conclusive evidence for or against the existence of causal relationships; rather, their usefulness lies in suggesting lines along which more detailed studies might proceed.

1.6 Radon Exposure and Smoking

Since smoking is a known cause of lung cancer (Doll and Peto, 1976), exposure to tobacco smoke has the potential to confound possible associations between lung cancer mortality and exposure to radon daughters. However, in addition to its rôle as a confounder, smoking may also modify the effect of radon daughter exposure. In a recent report, the Committee on the

Biological Effects of Ionizing Radiations (NRC, 1988) described how smoking-induced changes to the lung could influence the alpha-radiation dose from radon daughters. For example, dose might be increased by slowed mocuciliary transport or by enhanced deposition of particles; or alternatively, dose might be decreased by a thickening of the mucus layer in the respiratory tract. This last possibility has been discussed in detail by Axelson and Sundell (1978).

The interaction between smoking and radon daughter exposure has been investigated in epidemiological studies of miners, and also in studies of indoor exposure. Whittemore and Macmillan (1983) carried out a case-control study, with subjects chosen from the Colorado Plateau cohort of 3362 white uranium miners. Four living controls were selected for each of the 194 cases who had died from lung cancer. The study period ended on 31/12/77, although nine of the cases had died after that date. A proportional hazards model (Cox, 1972) was used to model the dependence of relative risk upon cumulative exposure to radon daughters (WLM) and cigarette consumption (packs), both lagged by 10 years. Radon daughter exposure was considered in six (i = 1,..,6) categories of WLM (0-21, 22-119, 120-359, 360-839, 840-1799, 1800+); smoking in four (j = 1,..,4) categories of pack years (0-10, 10-20, 20-30, 30+). A linear relative risk function of the form RR = 1 + β_{ij}, did not provide a statistically significantly better fit to the data than did the multiplicative function,

$$RR = \left\{1 + \beta_i^{radon}\right\} \left\{1 + \beta_j^{smoking}\right\}$$

(chi-square on 15 df = 13.41). Furthermore, replacing the indicator variables for exposure categories in the multiplicative function, by single degree-of-freedom linear trends, gave almost as good a fit (chi-square on 6 df = 5.18). The fitted trends were 0.31 per 100 WLM radon daughter exposure, and 0.51 per 1000 packs of cigarettes. The authors stressed that the findings of the study were of limited relevance to the situation of low-level exposure. Hornung and Meinhardt (1987) also used a proportional hazards model to analyse lung cancer mortality in the same cohort to the end of 1982. There were 69 more deaths, and cases were compared to all living controls at each time point of death. The authors used a power function to

represent the relative risk, i.e. RR = (WLM + background)$^{\beta}$. Once again, the best representation of the joint influence of radon daughter exposure and smoking upon the relative risk was by a multiplicative function. However, the risk estimates predicted by the fitted model were higher than those reported by Whittemore and Macmillan (1983).

The joint effect of radon daughter exposure and smoking has also been studied in Swedish mining communities. Axelson and Sundell (1978) identified 29 males who died from lung cancer between 1956 and 1976 in the parish of Hammer, which is situated near two zinc–lead mines. Six deceased referents were selected for each case, lung cancer deaths being excluded as referents. The mining company identified which of the 29 cases and 174 referents had worked underground. Smoking information was obtained, for miners only, from medical files and interviews with retired foremen; data were not available for two cases and three referents. The estimated relative risk of lung cancer (miners versus non–miners), allowing for age, was 16.6 (90% limits – 7.8 to 35.3). An adequate examination of interaction would have required smoking information for non–miners as well as miners, but the results implied that the risks of mining were higher for non–smokers than for smokers:–

	Non-miners	Miners	
		Non-smokers	Smokers
Case	8	9	10
Referent	155	3	13

The author suggested that a thickened mucus layer in smokers might be protecting the bronchial epithelium from alpha–radiation.

Radford and St Clair Renard (1984), in their cohort study of 1415 Swedish iron–ore miners (Section 1.2 above), also found higher relative risks among non–smokers. Expected numbers of lung cancer deaths were calculated for smokers and non–smokers separately, using results of a survey of the smoking habits of 25000 Swedish males. Results showed a less than multiplicative interaction:

	Observed	Expected
Non-smokers	18	1.8
Smokers	32	11.0

However, a different pattern of interaction, more in line with results of the recent analyses of the Colorado Plateau data, was reported by Damber and Larsson (1985) in a case-control study of lung cancer conducted in the northern Swedish municipalities of Kiruna and Gallivare. Iron-ore mines situated in the area provided the dominant industry locally, and exposure to underground mining was therefore expected to feature amongst study subjects. Cases were 69 male lung cancer deaths occurring between 1972 and 1982, and drawn from the Swedish Cancer Registry. There were two control series, one living (drawn from the National Population Register), and one deceased (drawn from the National Registry of Causes of Death). Information on smoking and occupation was obtained by interview of close relatives and living controls; measures of cumulative exposure were years worked underground and lifetime cigarette consumption. Analysis by a linear logistic regression model showed no interaction between the two exposures, a result consistent with a joint multiplicative effect. Relative risks between time-worked categories were:

	Time worked (years)		
	0	<20	>20
RR	1	2.5	8.9

and between smoking categories:

	Cigarettes smoked		
	0	<150000	>150000
RR	1	2.2	11.4

Morrison *et al* (1988), in their cohort study of 1772 Newfoundland fluorspar miners (Section 1.2 above), also found that risks of radon daughter exposure and smoking combined multiplicatively. Linear trends with radon daughter exposure were fitted to SMRs (expected numbers based on Newfoundland

rates) within four smoking categories - 'never smoker', ex-smoker, current smoker, and 'unknown'. Gradients did not differ significantly, and were equal to 0.4, 0.8, 0.5 and 0.7 per 100 WLM, respectively.

Several publications on the health effects of indoor exposure to radon daughters have provided information on the interaction with smoking. In Sweden, Edling *et al* (1986) reported further results from the case-referent study of Edling *et al* (1984, see Section 1.3 above), and suggested that their data were consistent with a multiplicative form of interaction:

Smoking Status	Average indoor Rn daughter concentration (Bq m^{-3})	
	< 50	⩾ 50
Non-smoker	1	2.6
Smoker	4.1	10.3

However, a different pattern was reported by Axelson *et al* (1988, see Section 1.3) in their study of 177 lung cancer cases and 673 referents, which was intended to reproduce the results of Edling *et al* (1984). In urban areas, relative risks were found to decrease with increasing exposure category 0, 1 and 2 (based on house characteristics) for both non-smokers and smokers, whereas, in rural areas, among non-smokers, passive smokers and occasional smokers combined, risks increased with increasing exposure. Risks for smokers in rural areas fluctuated, increasing to 1.5 (category 1) and then decreasing to 0.7 (category 2). The authors had no explanation to offer for the contrast between the urban and rural results. Interestingly, the clearest trend in relative risk across exposure categories 0, 1 and 2 was among female passive smokers (allowing for age, and urban-rural distribution). In contrast to this complex pattern, results reported by Svenson *et al* (1989, see Section 1.3) in their case-control study of lung cancer in Stockholm women, showed a positive interaction between the two exposures, somewhat less than multiplicative.

Finally, Schoenberg *et al* (1990, see Section 1.3), in their analysis of data from 433 female lung cancer cases and 402 controls in New Jersey, reported

a pattern of interaction rather reminiscent of that found by Axelson and Sundell (1976): relative risks in 'moderate' smokers increased with increasing radon exposure, but apparently declined in 'heavy' smokers:

Smoking Group	Radon concentration (pCi/litre)		
	<1.0	1.0-1.9	2.0-11.3
Lifetime non-smokers	1	0.9	1.2
<15 cigarettes/day	1	1.7	(6 cases, 0 controls)
15-24 " "	1	1.1	2.4
25+ " "	1	0.8	0.4

In discussion, the authors referred to experimental work on beagles which showed that high exposure to tobacco smoke protected against lung cancer induced by radon. However, they also stated that misreporting of smoking habit by next-of-kin could have biased exposure response relationships.

It is clear from this brief review of studies in which the joint action of cigarette smoking and radon daughter exposure has been investigated, that the question of the precise form of the interaction remains open. The BEIR IV Committee (NRC, 1988), in their review of the topic, assert that 'a clear pattern of risk ... has not yet emerged'.

1.7 Background to the Present Study

Coalminers were an occupational group whose mortality had not (by the mid 1980s) been studied in relation to radon daughters. Measurements of radon gas in 12 British coalmines (Duggan *et al*, 1968) had given an estimated median value of 20 mWL. At this level of exposure, a man working underground for one year would acquire a cumulative exposure of 0.2 WLM - far less than exposures in uranium and iron-ore mines. For example, Radford and St Clair Renard (1984) gave a figure of 4.8 WLM as the average annual exposure for Swedish iron-ore miners. Since results of the NRPB survey of British homes had shown average indoor levels of radon close to

those in British coalmines, it appeared that coal miners might be an appropriate group in which to study the health effects of low-level radon daughter exposure.

Studies of the mortality of British coalminers have shown a reduced lung cancer risk relative to the general population. In a review, Goldman (1965) summarized results of studies based on census and necropsy data, and also presented hitherto unpublished data acquired from National Coal Board sources, and the Epidemiological Unit of the Medical Research Council in South Wales. The Registrar General's Decennial Supplement on Occupational Mortality in England and Wales for 1949-53 had given an SMR of 0.71 for Miners and Quarrymen aged 20 to 65. In Scotland the corresponding figure was 0.80. There are well known biases involved in the use of occupational information on death certificates, for example a man's last job may not reflect the job held during most of his working life, or information obtained from the informant of the death may be unreliable. However, unpublished data from an enquiry carried out to investigate these biases showed a lung cancer SMR of 0.74 for coalminers in England and Wales for the year 1955, a result which agreed well with the Registrar General's figure. Goldman also quoted unpublished data from a follow-up of male inhabitants of a coalmining valley in South Wales, the Rhondda Fach, during 1951 to 1956. The SMR for lung cancer in 5096 miners and ex-miners was 0.81. Goldman concluded that there was convincing evidence of reduced mortality from lung cancer in British coalminers, which could not be accounted for by differences in smoking habit.

Liddell (1973) investigated the mortality of British coalminers for the year 1961. Deaths were identified from various sources - the Registrar General, the National Coal Board (collieries and Pensions Branch), and next-of-kin who were contacted through Medical Officers of Health. Death rates for working miners were calculated using a five percent sample census of the mining industry carried out in 1961. Lung cancer SMRs varied from 0.49 for Face Workers, through 0.53 for workers 'Elsewhere Underground' to 0.82 for Surface Workers.

Results of a 20-year follow-up, from 1950 to 1970, of 6212 non-miners, ex-miners and working miners resident in the Rhondda Fach, South Wales were reported by Cochrane *et al* (1979). All-cause mortality in non-miners was close to that expected (SMR = 0.99), but raised for miners and ex-miners. The SMR varied from between 1.16 and 1.20 for men whose radiological category at the start of follow-up was simple pneumoconiosis (CWP) category 0, 1, 2 or 3 or Progressive Massive Fibrosis (PMF) category A, to 1.95 for men with PMF category B or C. However, lung cancer mortality was reduced: SMRs were 0.66 for non-miners, 0.70 for men (miners and ex-miners) without CWP or PMF, 0.68 for men with CWP, and 0.80 for men with PMF.

A recent mortality study of approximately 25000 British coalminers showed that all-cause mortality over a 22-year period was 13% lower than that of males in the same regions of England and Wales (Miller and Jacobsen, 1985). Lung cancer SMRs were not calculated, but there was no evidence of an association, positive or negative, between dust exposure and lung cancer death rates.

Results of American studies have not given such a consistent picture of low lung cancer risk as those from Britain. Costello *et al* (1974) studied a randomly selected group of 3726 Appalachian coalminers over an approximately 10-year period from 1962/63 to 1972. Twenty-four deaths from lung cancer were observed compared to 36 expected on the basis of US rates for 1968, an SMR of 0.67. The authors contrasted their findings with those of Enterline (1972) who, from death certificates and census data, calculated a lung cancer SMR of 1.92 for US coalminers for the year 1950 (161 deaths observed compared to 84 expected). The study by Rockette (1977) of mortality in a group of 23128 men selected in 1959 as a 10% sample of members of a coalminers' health and retirement fund gave a result intermediate between those of Costello *et al* and Enterline. Over a 12-year period from 1959 to 1971, 352 deaths were observed from lung cancer, compared to 310 expected, an SMR of 1.13.

Despite the mixed American results, the predominating pattern of results in Britain suggested that any effect of underground radiation upon the lung cancer risk of British coalminers would be small.

The present study, using the accumulated resources of the British National Coal Board's Pneumoconiosis Field Research (PFR) was proposed to NRPB, in 1987. As part of PFR, the Coal Board, through the Institute of Occupational Medicine in Edinburgh (IOM), had maintained a long-term study of the mortality of approximately 30000 miners, employed at 24 collieries during the 1950s (Miller and Jacobsen, 1985). The proposed study was to be based on a subgroup of these men, augmented by another group of miners, all of whom had worked at 10 collieries (of the 24), where levels of radon daughters and also of thoron daughters had been measured in the 1970s. Thoron (radium-220), a radioactive isotope of radon, is formed as part of the decay chain of thorium-232. It decays through five daughters (isotopes of polomium, bismuth, lead and thallium) eventually reaching the stable lead-208. Much less is known about the health effects of thoron daughters; the associated risk of lung cancer is reckoned to be about one-fifth that of radon daughters (James, 1988). Its comparatively short half-life (56 seconds compared to 3.8 days for radon-222) means that less time is available for the gas to be transported to indoor or mine atmospheres before decay takes place (Nero, 1988). In a study of Norwegian niobium miners exposed to radon and thoron daughters, Solli *et al* (1985) reported excess lung cancer incidence compared to the Norwegian male population.

Exploratory analysis (by the IOM) of lung cancer mortality at the 10 collieries where radioactivity had been measured, showed that age-adjusted colliery-specific death rates had a statistically significant Spearman rank correlation coefficient with average radon daughter levels. To allow further exploration of this preliminary result, NRPB agreed to support the proposed study, which began in November 1988. The objective was to study relationships between exposure to low levels of radon and thoron daughters at 10 British collieries, and subsequent mortality, in particular from lung cancer.

2. MEN AND CHARACTERISTICS STUDIED

2.1 The Pneumoconiosis Field Research

The present research project sprang from the PFR. For a full account, see Jacobsen (1981); what follows is a brief summary, with particular reference to aspects relevant to the present study.

In 1952, the National Joint Pneumoconiosis Committee invited the National Coal Board to undertake a programme of research into the causes of pneumoconiosis. Twenty-five collieries were chosen to participate from all parts of the British coalfield - five from Scotland, six from South Wales, and fourteen from the regions of England, from Kent to Northumberland. The selection was not a random one; instead an effort was made to cover a range of dust conditions thought to be relevant to pneumoconiosis.

The two main 'arms' to the research were the medical surveys, and the environmental monitoring programme. Between 1953 and 1958, each of the 25 collieries was visited by one of two mobile X-ray units based at Cardiff and Edinburgh. This constituted the first round of medical surveys. Second and third rounds (1958-63, 1963-68) were carried out at 24 of the original 25 collieries, fourth and fifth rounds (1968-73, 1973-78) at 10 of these 24, and a sixth round (1978) at two of these 10. From the second survey onwards, a questionnaire on respiratory symptoms and smoking habits was administered. The aim throughout this series of surveys was to examine all coalminers currently employed at time of survey.

During the 1970s, a special study of miners and ex-miners (the so-called Follow-up Study) was undertaken at the 24 collieries surveyed in the second round. Medical examinations were conducted, which coincided with the fifth routine PFR survey at seven of the 24 collieries, and with the sixth at one other. At the remaining 16 collieries, separate surveys were organized. Participants in the Follow-up Study (i.e. men invited to attend Follow-up Survey) were a sample of men seen at first survey some 20 years earlier.

As the medical surveys were proceeding, a detailed programme of dust sampling was being carried out at the same collieries. Colliery populations were stratified into occupational groups on the basis of exposure to coalmine dust. An 'Attendance Records System' was devised to keep a record of times worked by individual men within occupational groups. During the 1960s, the Attendance Records System was computerized, and records of times worked were transferred to magnetic tape. Some summarization of data was carried out during this transfer: times worked within occupational groups were totalled within 'Inter Survey Periods' (ISPs), which were the approximately five-year periods between successive PFR surveys. Following computerization, records of times worked within occupational groups were kept on a quarterly basis.

(Some useful terminology may be introduced at this point. PFR surveys are referred to throughout by the letters PFR followed by the round number of the survey. PFR1, PFR2 and PFR3 together constitute Phase One of the Field Research; PFR4, PFR5 and PFR6, Phase Two. The 10 collieries where Phase Two surveys were conducted are collectively known as Phase Two collieries. The shorthand term 'ISP' has already been introduced; the period between PFR1 and PFR2 is called ISP1, between PFR2 and PFR3, ISP2, and so on. ISP0 refers to a man's coalmining experience prior to PFR1.)

Following PFR3, the Attendance Records System was maintained at the 10 Phase Two collieries only; and after PFR5, at nine of these 10, one colliery having closed in June 1973, shortly after PFR5. Although the final rounds of medical surveys were either the fifth (at eight of the 10 Phase Two collieries) or the sixth (at the other two collieries), the Attendance Records System continued for some time after PFR5 or 6. Thus, 'ISP5' Attendance Records times (spanning between 11 and 16 quarters) are available (for men in the present study) at nine collieries, 'ISP6' times (two to five quarters) at seven, and 'ISP7' times (one quarter) at one. With the exception of ISP5 at the two collieries where PFR6 was held, these 'ISPs' do not refer to inter-survey periods, and are regarded here merely as labels, indicating an approximate period during which time was worked. The latest year for which Attendance Records information is available from PFR computer files is 1980.

The purpose of the Attendance Records System was to record times worked in occupational groups at the PFR collieries; times worked at PFR collieries during ISP0, or at non-PFR collieries during any ISP, could not be recorded by this System. An attempt was therefore made to estimate these times by administering occupational history questionnaires at each round of routine PFR surveys to men falling into one of two categories:

i) those attending a PFR survey for the first time;

ii) those attending their second or later survey, but who had worked outside the PFR colliery since they had last been seen.

Information recorded on occupational history forms was summarised, and subsequently computerised, in the form of time worked, within ISP, in six broad categories of coalmining activity. Time outside mining was also included, and categorised as 'noxious' or 'non-noxious', in respect of likely exposure to airborne substances which could conceivably be associated with risk of lung disease.

Occupational history questionnaires were in fact administered to a third group of men, but only during Phase Two of the PFR. These were men whose time information (both Attendance Records and occupational history) gathered during Phase One was not transferred to computer in the 1960s, because of the then unmanageable size of the data processing task. At that time, the decision was taken not to process time-worked data for men who had attended only PFR1 or 2 (but not both) in Phase One, the so-called 'Singletons'. These men, it was felt, could not contribute to a study of radiological change over the first three surveys, and their time records were dispensed with. Any Singletons attending PFR4, 5 or 6, or Follow-up Survey, were therefore asked to complete an occupational history questionnaire. The resulting data were used to fill gaps in their time records for ISPs 0, 1 and 2.

2.2 Men participating in the Present Study

The present study evolved from earlier PFR-based research into coalminers' mortality - see, for example, Miller and Jacobsen (1985). These authors studied 31647 miners who attended PFR1 at 24 of the 25 participating collieries where second and third survey rounds were later conducted. (PFR1 attenders comprised about 90% of the coalminers employed at the 24 collieries at time of survey.) By 1970, identifying information for the 31647 men had been sent to the Office of Population Censuses and Surveys (OPCS) in England and Wales, and the Registrar General's office in Scotland, in order that searches for their records could be made in the National Health Service Central Register (NHSCR). By methods which are described in more detail below, the IOM was notified of deaths which had occurred in this group of men between PFR1 and the date of search. Details of subsequent deaths were supplied to the IOM as they occurred, and the notification procedure is still active at the present time (1992). Of the 31647 men, 15188 who attended PFR1 at one of the 10 Phase 2 colllieries were included as participants in the present study. The restriction was necessary, because radioactivity data were available only for Phase 2 collieries. A further 4230 men who attended PFR2, but not PFR1, at the same 10 collieries were also included; their identifying information was sent to OPCS and the Registrar General's office in 1988. Inclusion of this second group (giving a total cohort of 19418 men) boosted the power of the study, and also increased the proportion of men for whom smoking information was available, since the PFR respiratory symptoms questionnaire was not introduced until PFR2.

2.3 Mortality Data

Notifications to the IOM of deaths in the study population were accompanied by copy death certificates, with the underlying cause of death coded according to the International Classification of Diseases (ICD) (World Health Organization [WHO] 1957; WHO, 1967; WHO, 1977). Three revisions of the ICD came into force during the study period, the Seventh, Eighth and Ninth in 1958, 1968 and 1979 respectively. However, the earliest deaths in the subset of the study group considered for the present report - some

exclusions were made because of unreliable or missing data – occurred in 1958. It was only necessary, therefore, to express the causes of death of interest in terms of the Seventh, Eighth and Ninth Revisions. These causes, with ICD codings, are given in Table 2.1.

With two exceptions (oesophageal and laryngeal cancer), excess mortality from each of the causes in the Table has been found in previous studies of radon daughter exposure. The two extra causes were included because it seemed plausible that the anatomical sites concerned would be liable to some degree of exposure to coalmine dust, and therefore, potentially, to radon and thoron daughter atoms attached to dust particles. It should be noted that, of all the causes listed, only lung cancer has been demonstrably linked to radon daughter exposure. Evidence of association derived from correlation studies in particular must be regarded with special caution.

2.4 Radon and Thoron Daughter Exposures

Men's exposures to radon and thoron daughters were estimated using data from two sources. First, the Attendance Records System and Occupational History Questionnaires of the PFR gave estimates of times worked within occupational groups and six broad classes of coalmining activity, respectively. These were combined with data from the second source, a survey of radiation levels carried out at the 10 Phase Two collieries (and one other non-PFR colliery, whose data were not used) during the 1970s and 1980.

During the early 1970s, a draft 'Euratom' directive on ionising radiation was in preparation, and it was the need to assess the implications of this directive for British coalmines which prompted the radiation survey. One hundred and sixty-one measurements of radon and thoron daughter levels were made at 11 collieries between April 1972 and June 1980, of which 146 were at PFR collieries. A method developed by Ogden (1974) was used to obtain the measurements. It had the advantage of using the Mining Research Establishment's type 113A respirable dust sampler, which was a routine PFR device. Furthermore, from a single dust sample, estimates of both radon and thoron daughter levels could be obtained, these levels referring to shift

averages, and not to specific points in time during shifts. (However, the averages were heavily weighted towards the shift-end. According to Ogden, the first five hours of a seven-hour shift had a cumulative weight of only one quarter.)

The results of the survey were reported in detail by Crawford and Edlin (1982), and part of their data is reproduced in this report in Appendix 2. As well as both radon and thoron daughter levels, these authors gave the location underground where samples were obtained, the barometric pressure, weight of dust in the sample, length of shift, and the distance underground travelled by the ventilating airstream from the foot of the colliery shaft to the sampling site (known as the ventilation distance). Of these, only radioactivity levels, ventilation distance, and the coal seam in which samples were obtained, are given in Appendix 2. One other variable is listed - the ventilation quantity (m^3 sec^{-1}) at the sampling site. This parameter was not measured by Crawford and Edlin; the quoted values are coalface annual averages for the years in question. These were obtained from annual PFR reports of environmental conditions at research collieries, and were not available for some of the sites where radioactivity samples were taken, and, of course, for the non-PFR colliery (colliery H in Appendix 2).

2.5 Smoking Habit

A questionnaire on respiratory symptoms was clerk-administered at every round of PFR surveys, except PFR1. A copy is given in Appendix 3. Five of the six items on smoking referred to current habit; the sixth was asked only of current non-smokers, to establish if they had smoked at any time prior to survey. The questionnaire therefore allowed the identification of three groups at each PFR survey: non-smokers (these men had also never smoked prior to survey), ex-smokers (current non-smokers, who had, however, smoked at some time prior to survey) and smokers (a group which included both cigarette and pipe smokers). In the latter group, further subdivision by amount smoked was carried out; details are given below.

Table 2.1 Causes of death examined in relation to radon and thoron daughter exposure.

Cause of death	ICD Coding		
	7th Rev.	8th Rev.	9th Rev.
Malignant neoplasm of:			
oral cavity	140-148	140-149	140-149
salivary gland	142	142	142
oesophagus	150	150	150
stomach	151	151	151
larynx	161	161	161
trachea, bronchus and lung	162	162	162
bone	196	170	170
Malignant melanoma	190	172	172
Malignant neoplasm of:			
prostate	177	185	185
kidney	180	189	189
Leukaemia (excluding chronic lymphoid)	204 (excl. 204.0)	204-207 (excl. 204.1)	204-208 (excl. 204.1)

3. METHODS

3.1 Establishing Vital Status

Following dispatch to OPCS of identifying information on the members of the study group, searches for their NHS records in the Central Register were carried out by OPCS staff.

Copies of death certificates for men who had already died were dispatched to the IOM. Records of men who were alive were 'flagged' with a symbol identifying the present mortality study. As these men died during the course of the study, the presence of flagged NHSCR records ensured that copy death certificates were sent to the IOM. The underlying cause of death appearing on certificates was coded according to the ICD. Seventh or Eighth Revision codings were used for decedents who had attended PFR1; otherwise, the Ninth Revision was used.

By August 1990, the vital status of approximately 4% of the study population was still unknown, or uncertain. An attempt was made to reduce this percentage using the letter forwarding service of the Department of Social Security (DSS). Letters to selected study group members of unknown vital status were prepared, requesting that they notify the IOM of their current address. These were sent to the DSS, who forwarded them, whenever possible, to addresses currently held at DSS. (The IOM were not given the addresses to which forwarded letters were sent.) In addition, dates of death were supplied to the IOM for men who had died according to DSS records. As a result of this exercise, approximately 100 of these men were confirmed alive. Updated identifying information (ie. new or corrected addresses) was sent to OPCS, so that a fresh search could be made for their records in the NHSCR. In statistical analysis, these men were regarded as alive up to 31/12/1989. Updated information on vital status (ie. dates of death) was also prepared, for men confirmed dead by DSS, and dispatched to OPCS. However, computer files of mortality information had been 'frozen' for purposes of statistical analysis before copy death certificates, with ICD codings,

had begun to reach the IOM, and hence, in analysis, they were regarded as 'untraced', and excluded.

The DSS were unable to forward letters to approximately 300 men, either because they could not identify them, or because they did not hold an address. The National Concessionary Fuel office of the British Coal Corporation were asked to search their own records, and also Pension Fund records, for these men, and where possible, to forward letters on the IOM's behalf. For cost reasons, the search was limited to a random sample of 50 men, in the first instance. This work is currently in progress. It has not been possible to include in the present analysis any of the results of these searches.

According to OPCS, about one-fifth of the 4% of the study group whose vital status was unknown at August 1990, had left the UK. Dates of embarkation were available, but it has not been possible to process these for the present analysis. It would have been preferable to include the men, and regard the date of embarkation as a date of loss to follow-up. They have, however, been excluded from statistical analysis.

3.2 The Calculation of Radon and Thoron Daughter Exposures

3.2.1 Introduction

One of the most striking features of the data on which calculation of working-time exposure in this study were based, is the contrast between the superabundance of information on time worked - both durations and locations - and the paucity of information on radon and thoron daughter levels. Data on time worked (ie. Attendance Records and Occupational Histories) comprise some hundreds of thousands of records; for coalface workers in particular, the information provided specifically by Attendance Records is extremely detailed. Thus, it is possible to establish for each man employed at the coalface during the PFR research, the faces at which he worked, and for how long. Also, such times worked are available by inter-survey period in Phase One, and by quarter in Phase Two.

Radioactivity data, on the other hand, are extremely sparse, consisting of 161 measurements at 11 collieries, with 15 of these at a non-PFR colliery. Of 896 coalfaces listed in the PFR History of Faces, measurements of radon and thoron daughters used in this study were made on only 42; of 42 coal seams listed, measurements were made in only 20. Furthermore, at nine of the 10 research collieries, surveys of radioactivity were carried out over short periods of only a few months during the 1970s (see Appendix 2). The one exception was at colliery Q, where a first series of measurements made between April and November 1972, was followed by a second during June and July 1979, and a third between April and June 1980.

In view of the few radioactivity data available, the strategy adopted for calculation of exposure was to average radon and thoron daughter measurements within individual coal seams, and to use the resulting means as estimates of the radioactivity level applying to any Occupational Group working in the seam. The rationale was that rocks surrounding coal faces in a single seam would often have fairly similar mineralogical compositions. Since radon and thoron gas concentrations would depend on the ore-types present in the rock (as well as many other factors - ventilation regimes, amount of ground water, type of mining method etc.), areas located in the same seams might be expected to be closer in radon and thoron daughter level, on average, than areas in different seams. This method was preferred to a simpler scheme, whereby a single mean radioactivity level would have been assigned to all underground work at each colliery. Table 3.1 shows mean levels of radon and thoron daughters, by seam. Differences between seams are sufficiently large to suggest that seams should be distinguished in exposure calculations. The statistical significance of seam differences (on the log scale) was examined using analysis of variance (Tables 3.2 and 3.3); results showed that the differences in radioactivity level were significant at the 0.001 level.

3.2.2 Overview of the method of calculation

The total time worked in coalmining by each man in the study group with time-worked information, was partitioned into several 'risk categories'.

Average radon and thoron daughter levels were assigned to each category, and cumulative exposures calculated by summing the products: average level by time worked, over all categories. This calculation was carried out by ISP, so that men's cumulative exposures were finally available in roughly five-year 'packages', corresponding to ISPs. (However, ISP0 exposures were of variable calendar-time duration, depending on the date prior to PFR1 when men began work in coalmining.)

3.2.3 Definition of risk categories

Attendance Records time at each colliery (i.e. time worked within PFR Occupational Groups, and recorded in the Attendance Records System) was partitioned first into surface and underground time. The latter was further subdivided by coal seam. Two other underground categories introduced were: 'All Seams', which included time spent in mobile jobs, not specific to single seams; and 'Pit Bottom', which covered time spent in jobs at or near the foot of the main shaft. The complete list of these categories is given in Table 3.4.

Occupational History time (i.e. men's own estimates of time worked given at interview during routine PFR surveys, or at Follow-up Survey) was divided into four categories: time worked underground at the research colliery (the colliery where the survey was being conducted); time worked on the surface at the research colliery; time worked underground at non-PFR collieries; and time worked on the surface at non-PFR collieries.

3.2.4 Assignment of radioactivity levels to risk categories

Attendance Records time allocated to a seam where radioactivity measurements had been made was assigned the mean radon and thoron daughter level for the seam. Time in seams with no measurements was assigned the mean level for the research colliery. The two remaining categories of underground Attendance Records time (i.e. 'All Seams' and 'Pit Bottom') were also assigned the colliery mean. Attendance Records time spent on the surface was

assigned estimated outdoor concentrations of radon and thoron daughters, a single value of each being used for all 10 collieries. Estimates were provided by the National Radiological Protection Board (NRPB). It was considered unnecessary to distinguish indoor from outdoor surface work, since most 'indoor' industrial jobs would have been carried out in well-ventilated sheds. Table 3.4 also gives the radon and thoron daughter levels specific to Attendance Records time categories.

Time worked underground and on the surface at the research colliery which was recorded on Occupational History questionnaires, was assigned the colliery mean level and the estimated outdoor concentration, respectively. Time worked at non-PFR collieries was treated in the same way, the rationâle being that many of the men 'migrating in' to PFR collieries would have come from neighbouring collieries working the same coal seams.

3.2.5 Partitioning of Attendance Records time

Times worked by individual men within Occupational Groups were available on computer file, by ISP. For ISPs 1 and 2, the data were held as total times within ISP; times worked during ISPs 4 to 7 were available quarterly. ISP3 times were available quarterly for some Occupational Groups, and as ISP3 totals for the remainder. Before partitioning times into risk categories, quarterly information was totalled within ISPs 3 to 7 to give a uniform structure to the data.

The PFR History of Faces gave the correspondence between Occupational Groups (between 342 and 914 per colliery) and seams worked, during PFR. These data were computerized, and programs written to accumulate time worked in seams.

Some Occupational Group codes appearing in the computer files of Attendance Records time were not listed in the History of Faces. Further investigation of PFR documentation, and discussions with former PFR Investigators (staff who had been stationed at research collieries to oversee dust sampling) established that some of these unlisted codes had been devised locally to cover

such contingencies as 'away on course at Technical College' or 'temporarily attached to another works'. However, there remained a few codes which could not be accounted for, and time worked in these Occupational Groups was allocated to an 'unknown' category.

Units of measurement on Attendance Records files were 'numbers of normal shifts'; overtime was recorded separately, as hours worked. Conversion factors from shifts to hours were 7.5 for ISPs 1 and 2, and 7.25 for ISPs 5, 6 and 7, at all collieries. There was no single date on which the shift length was reduced at all collieries; 1st January 1973 has been taken as representative. The conversion factor for shifts worked in ISPs encompassing this date (ISP3 or ISP4 at all collieries) was taken as the mean of 7.5 and 7.25, weighted according to the approximate proportions of the ISP falling before and after 1/1/73.

3.2.6 Partitioning of estimated working times derived from Occupational Histories

These data were held on computer file as times worked within six categories of coalmining activity, by ISP. For the present study's purpose, the categories were collapsed into two: time underground, and time on surface. Also, time worked at PFR collieries was distinguished from time at non-PFR collieries, thus allowing working time to be partitioned into the four risk categories already mentioned.

All ISP0 times, and times in later ISPs which had been obtained at Phase 2 surveys or at Follow-up Survey in order to fill gaps caused by the disposal of Singletons' data, were held on computer file in units of years worked. A factor of 1740 working hours per year was used to convert to hours (48 weeks of 7½ hour shifts, with eight public holidays). Times in ISP1 and ISP2 which were obtained at Phase 1 surveys (which referred exclusively to non-PFR collieries) were held on computer file in units of hours worked. No conversion was required.

3.2.7 Calculation of exposures - an example

Details of the calculations described above are presented here for a randomly selected Study Group member at Colliery F.

Table 3.5 shows times worked by this man within Occupational Groups, by ISP, essentially as held on computer file. (Most men in the study did not have such a long employment record; the example was chosen with this feature in mind.) Total times worked (column 5) were calculated by applying a conversion factor to Normal Shifts (column 3) and adding overtime, if any. ISP3 at this colliery ended in April 1972; shift lengths of 7.5 and 7.25 hours were assumed for ISP3 and 4 respectively. The right hand column shows the risk categories into which time worked was allocated. Table 3.4 gives a key to the codes.

For this man, Occupational History time was recorded only for ISP0. Table 3.6 shows that he accumulated time in two of the four available risk categories during this period. The results of accumulating Attendance Records time within risk categories, and combining with Occupational History time, are shown in Table 3.7. The final step in exposure calculation was to multiply times within risk categories by the assigned radon and thoron daughter levels, shown in Table 3.4. Results are given in Table 3.8, both by ISP, and cumulatively.

3.2.8 Radioactivity surveys at two collieries

Estimates of cumulative exposures to radon and thoron daughters for this study were based entirely on radon and thoron levels measured in the 1970s and reported by Crawford and Edlin (1982). The method of estimation made no allowance for possible variations in level with calendar time; only at colliery Q were there sufficient data to allow examination of trends over periods greater than a few months. To test the assumption, implicit in the method of estimation, that the radioactivity measurements made in the 1970s could be regarded as representative of stable long-term seam levels, two surveys of radon and thoron daughters were carried out jointly by NRPB and British

Coal at collieries Y and C during May and August 1990 respectively. A track etch technique developed at NRPB was used (Miles, NRPB, Personal communication). Results are given in full in Section 4.3.4; for convenience, a brief summary is given here. The mean radon daughter level measured in 1990 at colliery Y was 7.4 mWL (s.d. 6.2, based on 24 measurements); the 1978/79 level was 5.3 mWL (s.d. 2.6, 15 measurements). Corresponding values for colliery C were 18.5 mWL (s.d. 7.5, 26 measurements) in 1990, compared to 4.0 mWL (s.d. 3.0, 10 measurements) in 1976/77. Thoron daughter levels measured in 1990 exceeded those of the 1970s by factors of $3\frac{1}{2}$ at Y, and 2 at C.

Only one other colliery (F) of the 10 Phase 2 collieries was still open at the time these measurements were made, but it was not included in the 1990 surveys, since its closure was imminent. However, at various times during the 1980s, measurements of radon gas activity concentrations were made at several of the Phase 2 collieries. From these data, estimates of radon daughter levels have been obtained using assumed values of equilibrium factors (Page, British Coal Scientific Services, Personal communication, 1990), and these results are also presented in Section 4.3.4.

3.2.9 Indoor exposures for the study group

Since radon gas is present to a varying extent in indoor air (and in outdoor air, but at lower levels), cumulative exposure to radon daughters outside working hours will have been acquired by the men in the study group. No account was taken of this component of exposure in analyses of mortality, since no data were available on radon levels in the miners' homes, or on the proportions of non-working time spent indoors. However, an attempt was made to calculate a rough estimate of the magnitude of indoor exposure, using data from a survey of radon levels in 2000 UK homes carried out recently by NRPB (Wrixon *et al*, 1988). (A similar exercise for thoron daughters was not attempted due to lack of data.)

Mean radon levels reported by Wrixon *et al* for counties in which the PFR collieries were situated were converted to radon daughter levels, in mWL,

assuming an equilibrium factor of 0.5 (Table 3.9). These were multiplied by appropriate factors to give an estimate of the mean cumulative exposure to radon daughters, due to indoor radon, acquired by men working at the research collieries. Exposure was calculated up to the average ages, by colliery, for which the latest records of exposure were available from PFR data. This was done to allow a direct comparison with total cumulative exposure gained during working time. The factors used in the calculation were estimates of the proportion of time spent indoors by working miners, and also by children (to take account of ages 0 to 15), and were based on occupancy estimates given by Wrixon *et al.* These authors reported an average indoor occupancy of 92%, a figure which included both sexes. Since housewives were reported as spending more time indoors (97%), it seems likely that the male population will spend slightly less time indoors than the overall average, say 87%. Miners spending approximately one-third of their working days at the colliery could have an occupancy of no more than approximately 67% on working days. The overall occupancy for a working miner was therefore estimated as

$$5/7\ 67\% + 2/7\ 87\% \simeq 70\%.$$

The corresponding occupany for ages 0–15 was taken as 90% (using the overall average occupancy).

Cumulative exposures were calculated using the formula:

$$[\ (15 \times 0.9) + (AGE-15 \times 0.7)\ ] \times mWL,$$

where mWL denotes the county mean level of radon daughters, and AGE, the chosen age to which exposures were calculated for each colliery.

3.3 Smoking Habit

For the present statistical analysis, men's smoking habits at each PFR survey at which they provided valid data were coded according to the following scheme:

Smoking habit	Code
Non-smoker	1
Ex-smoker	2
Pipe smoker	3
Cigarette, or cigarette and pipe smoker:	
Equivalent of 1 to 5 cigarettes per day	4
" " 6 to 10 " " "	5
" " 11 to 20 " " "	6
" " 21 to 30 " " "	7
" " 31 to 40 " " "	8
" " over 41 " " "	9

Note that, since a code was calculated for each survey at which a man provided information, his code could change throughout the follow-up period. Details of the implementation of the coding scheme are given in Appendix 4.

3.4 Definition of Risk Period

Only men with adequate radon and thoron daughter exposure data, and data on smoking habit, were included in analyses of mortality; and this restriction had implications for setting the starting date of the risk period for individual men. In general, a man entered the period of risk at the earliest PFR survey by which all the non-mortality information essential for his inclusion in the analysis had been gathered. The implications are considered first for time-worked information, and then for smoking.

The fact that Singletons' time-worked information gathered during Phase One was discarded prior to computerization, has already been mentioned. However, it was possible to include some Singletons in analyses. At three of the 10 research collieries (P, Q and V), computerization of time-worked information gathered in Phase One was in fact completed before the decision to discard data was made. Singletons' time information at these collieries was therefore available, and they were, in principle, considered to be at risk following their first attendance. Singletons included in analyses from the

other seven collieries were those who subsequently attended a Phase Two survey. At this second attendance, an Occupational History was taken, upon which estimates of time worked during ISP0, 1 and 2 were based. These men were therefore considered at risk following their earliest Phase Two attendance. Non-Singletons at collieries other than P, Q and V were considered at risk following their second attendance in Phase One, since it was the fact of their second attendance which guaranteed the retention of their time-worked data, and hence their inclusion.

The requirement that smoking information be available for men included in mortality analyses implied that they were not considered at risk of dying until their attendance at a PFR survey at which a respiratory symptoms questionnaire was administered. In general therefore, the start of follow-up was no earlier than PFR2. At colliery P, where an administrative error resulted in no valid smoking data being obtained at PFR2, the start was no earlier than PFR3. For some men - for example, Singletons who attended PFR1, or any Singletons at colliery P - the start of follow-up was the earliest attendance in Phase Two.

These considerations are summarized in Table 3.10, which shows dates of entry for various subgroups of the study population.

Dates of exit were either dates of death, or, for survivors, the end of the study period, 31/12/89.

3.5 Statistical Methods

3.5.1 Person-years at risk

Associations between radon and thoron daughter exposure and mortality from the two commonest cancers found in the study population, lung cancer and stomach cancer, were investigated first by the person-years-at-risk method (Breslow and Day, 1987). A description of the implementation of the method in the present study follows.

Each calendar year in which each member of the study group was at risk of death was added to the cells of two tables of person-years, one for radon daughter exposure, the other for thoron. Person-years tables were five-dimensional, and were indexed by calendar time, age, smoking habit, colliery of employment and exposure (radon or thoron). Only one aspect of radon and thoron daughter exposure history was used in analyses, namely cumulative exposure, considered as a time-dependent variable, and lagged by 10 years. No attempt was made to estimate a cumulative exposure to tobacco smoke, since respiratory symptoms questionnaire items referred to current smoking habit only, apart from a single question to identify ex-smokers. Current smoking habit was therefore used in analyses as a time-dependent variable lagged by five years.

Tabulation for a given man was carried out by determining values of the five classifying variables pertaining at the start of each calendar year during which he was at risk. For example, tabulation of year 1970-71 required determining his age on 1/1/70, his cumulative exposure to 1/1/60, and his smoking habit on 1/1/65. Calendar time itself required no calculation, and colliery of employment was taken to be time-invariant. (Of course, men could change their colliery of employment; a man who transferred from one PFR colliery to another would have been given a new Pit X-ray number, and, as far as the present analysis is concerned, would have been treated as a different subject. However, it is believed that such instances were rare. PFR collieries were originally chosen to provide a cross-section of the British coalmining industry, and were therefore not located in close proximity to each other.) Categorized versions of these variables were then derived, and the person-year added to the appropriate cell of each of the two tables. Table cells were defined thus:

Calendar time: 1954-59, 1960-69, 1970-79, 1980-89;

Age: -34, 35-44, 45-54, 55-64, 65-74, 75-;

Lagged smoking habit: non-smoker, ex-smoker, pipe smoker, cigarette smoker 1-10 per day, 11-20 per day, more than 20 per day;

Colliery: C, F, K, P, Q, T, V, W, X, Y;

Lagged cumulative exposure to radon or thoron daughters (WL hour):	0–, 25–, 50–, 100–, 200–, 400–, 800–.

(Note, in passing, that the categorization of cigarette consumption followed the coding system adopted when Phase One data were computerized – see Appendix 4.)

Tabulation of part–years was carried out only at the beginning and end of the risk period. Values of classifying variables were those pertaining at the date of entry, and 1st January of the calendar year of exit, respectively.

Given the structure of the exposure data (Table 3.8 shows a typical record of exposure), it was necessary to interpolate to obtain estimates of cumulative exposure to arbitrary time points between dates of entry and exit. Linear interpolation gave estimated cumulative exposure to the start of any calendar year within the record of exposure. Cumulative exposure to dates prior to the earliest date in the record of exposure was not estimated; thus, person–years were not allocated during the first 10 years of any man's record of exposure. Cumulative exposure to dates later than the end of the record of exposure was assumed equal to the final, highest, value in the record of exposure.

Similar procedures were used to estimate men's smoking habit, as one of nine category–codes, at arbitrary time points. For calendar years between PFR surveys at which valid questionnaire responses were obtained, data from the nearest survey provided estimates. Smoking categories for years before the earliest, or after the latest attendance at a PFR survey, were assumed equal to those pertaining at the earliest or latest attendance respectively.

Numbers of deaths from the two causes of interest were also tabulated, by the same variables classifying person–years tables. Lagged cumulative exposures and smoking categories were estimated at the start of the calendar year in which death occurred. Division of tables of numbers of observed deaths by tables of person–years, gave tables of cause–specific death rates.

The joint influence of exposure (radon daughter or thoron daughter) and other factors, such as age and smoking, upon death rates, was examined by fitting statistical models to tables of observed deaths and person-years. Numbers of deaths in table cells were assumed to follow the Poisson distribution with means equal to the product of the underlying death rate for the cell (per 100000 person-years) and the person-years-at-risk. Underlying death rates were assumed to be linear functions of explanatory variables, on the natural log scale. The discrepancy between within-cell death rates predicted by statistical models, and those observed, was measured by the so-called deviance statistic, given by the expression,

$$\text{Deviance} = 2 \sum \left[y \log \frac{y}{\mu} - (y - \mu) \right],$$

where y denotes numbers of deaths within table cells, μ the number of deaths predicted by the regression model, and summation is over the cells of the person-years table.

In model fitting, stratifying variables were always treated as categorical, and represented by groups of binary indicator variables. Exposure was sometimes treated as a categorical variable, and sometimes as a continuous variable; the text makes clear which representation is being considered. For the latter method, used specifically to examine trends, values were assigned to each cell of the person-years table, equal to the mean exposure over all person-years, or part years, allocated to the cell. Tests for trend were also carried out using the natural logarithm of exposure. A two-way interaction between categorical variables was represented in the usual way by a group of binary indicators, each indicator consisting of the product of one of the indicators representing the first variable, with one of the indicators representing the second. An interaction between a stratifying variable and a continuous exposure, was represented by a group of variables, each consisting of the product of a binary indicator with the exposure variable.

The statistical significance of a main effect or an interaction on death rates was assessed by computing the reduction in the deviance obtained by adding the main effect or interaction to an existing regression model. Under the

null hypothesis, this reduction was assumed to have a Chi-square distribution. Degrees of freedom were given by the number of variables representing the main effect or interaction.

The model-fitting strategy adopted was first to fit an additive model (ie. main effects only) comprising the stratifying variables age, calendar time, lagged smoking habit and colliery. All six two-factor interactions were then added, singly, and any found to be significant at the 5% level were included. Then, main effects for lagged radon or thoron daughter exposure, considered both as categorical and continuous variables, were added. Two-factor interactions between exposure and stratifying variables, taken one at a time, were investigated, exposure again being considered both as a categorical and a continuous variable.

Tables presented for each of the two causes of death considered include analysis of deviance tables, and tables of predicted death rates. The latter show death rates estimated by statistical models which contain stratifying variables, and significant interactions between them, together with exposure variables. To display a main effect or interaction, other variables in the model (not interacting with the effects to be displayed) were given arbitrary values. These values were:

Calendar time: 1970-79

Age: 55-64

Lagged smoking habit: 1-10 cigarettes per day

Colliery: Q

Lagged cumulative exposure to
radon or thoron daughters (WL hour): 0-25.

The person-years method was also used to compare death rates in the study group, from all causes and from lung cancer, with those in the general male populations of the geographical regions in which the research collieries were located. Regional population figures, and numbers of deaths, both by 10-year age group, were obtained for each year of the risk period from OPCS publications (1974 onwards), Annual Reports of the Registrar General

for England and Wales (pre–1974), and Annual Reports of the Registrar General for Scotland. From these data, general population death rates specific to age, calendar year, and region, were calculated. The total person–years lived by the study population was tabulated, exactly as described above, but by age, calendar year, and research colliery only (smoking and radon or thoron daughter exposure were not used in this classification). Numbers of deaths expected in the study population if regional rates had applied, were calculated by multiplying person–years at risk within table cells, by the death rate appropriate to the age, calendar year, and colliery classifying the cells, and summing over all cells. Division of the observed number of deaths by the total expected yielded standardized mortality ratios (SMRs). Age–specific SMRs were also calculated; for this purpose, numbers of observed deaths were tabulated by age at death. Statistical significance of SMRs was assessed by noting whether 95% confidence intervals enclosed unity. Gardner and Altman (1989) discuss the construction of confidence intervals for SMRs.

3.5.2 Case–referent studies

Associations between radon and thoron daughter exposure and mortality from all 11 causes of death listed in Table 2.1 were investigated in a series of case–referent studies. The idea of selecting cases and referents from a larger cohort was first suggested by Thomas, in an addendum to a paper by Liddell *et al* (1977); a full account is given by Breslow and Day (1987).

Men who died (cases) from one of the causes of death being investigated were grouped into strata according to values of four variables: age at death (recorded as an integer); quinquennium of calendar time when death occurred; smoking habit (coded as one of nine categories) pertaining at the birthday before death, lagged by five years; and colliery. Each stratum defined a set of potential referents, who were men at risk at the age of stratum cases, and matched to them in respect of colliery of employment, lagged smoking category (in nine categories) and calendar time (in quinquennia). For example, a stratum containing cases from colliery C who died aged 55 during 1960–64 and who smoked 6–10 cigarettes per day on

their 50th birthday, defined as potential referents, all men from colliery C at risk aged 55 during 1960–64, who smoked 6–10 cigarettes on their 50th birthday. Continuing the example, men who died aged 55 from a cause other than that of stratum cases were not excluded as potential referents. Neither were men who died after age 55 from the cause being investigated. Similar rules to those of the person–years tabulation were followed with regard to extrapolation and interpolation of cumulative exposures and smoking habit. In particular, cases and potential referents whose exposures could not be estimated were excluded from analysis.

Not all potential referents were included in case–referent comparisons. Referents for lung cancer and stomach cancer were randomly selected within strata, case–referent ratios being, respectively, 1 to 4, and 1 to 10. For other causes of death, all potential referents were chosen.

Comparison between cases and referents was, for all causes except one, of cumulative exposure to radon and thoron daughters, lagged by 10 years, to the last birthday before the cases' age – a lag of 10 years has been used in recent analyses of US uranium miners' mortality (National Research Council, 1988). The single exception was the comparison of leukaemia cases and referents, where a shorter lag of two years was thought appropriate, in line with the results of Darby *et al* (1987). Lung cancer cases and referents were also compared in respect of a combined measure of dose, derived from the formula (O'Riordan, NRPB, Personal Communication, 1989):

$$\text{dose in milli sieverts (mSv)} = 10 \times \text{lagged (10 years) radon daughter exposure (WLM)} + 3\,1/3 \times \text{lagged (10 years) thoron daughter exposure (WLM).}$$

Associations between case–referent status and exposure (or dose) were investigated first by descriptive methods. Within each stratum, the difference between case means and referent means was computed. The unweighted average of these differences over all strata was then calculated, with an estimate of standard error, as follows:

$$\bar{d} = \frac{\sum d}{n}$$

$$s.e.\ (\bar{d}) = \sqrt{\left[\frac{\sum (d - \bar{d})^2}{n\ (n - 1)} \right]}$$

where d denotes within-stratum difference, n denotes the number of strata, and summation is over all strata. Tests of significance were carried out by referring

$$\bar{d}/s.e.(\bar{d})$$

to the 't' distribution on n-1 degrees of freedom. These statistics were also computed for groups of strata defined by age, quinquennium, colliery of employment and lagged smoking category.

Analyses were also carried out using multiple conditional logistic regression analysis (Breslow and Day, 1987). Within strata, the logarithm of the odds of being a case was assumed to be a linear function of lagged cumulative exposure to radon or thoron daughters. Regression coefficients were estimated by the method of maximum likelihood; they measured the change in odds on the log scale expected from a unit increase in exposure. (When death rates are comparatively low, as in the present study, ratios of odds are good approximations to relative risks.) Likelihood ratio tests were used to assess statistical significance.

Since cases and referents were matched, the effect of exposure upon relative risks was automatically adjusted for the effects, if any, of age, calendar time, colliery and smoking habit. Indeed, the effects of these variables on mortality could not be estimated in this analysis. However, it was possible to investigate interaction between exposure and stratifying variables. For example, eight binary variables were defined, indexing the smoking categories, ex-smoker, pipe smoker, cigarette smoker 1-5 per day, 6-10, 11-20, 21-30, 31-40, and over 40. Products of these binary variables with exposure were computed, and a regression model fitted, which included an exposure term, and all eight product terms. A likelihood ratio test of the joint significance

of the coefficients of the product terms, allowing for an overall effect of exposure, yielded a test of significance of the interaction of smoking with exposure. The coefficient of the exposure term yielded the relative risk per unit of exposure, for non-smokers. Addition of this coefficient to that of any product, yielded relative risks within other smoking categories. Interaction between exposure and colliery of employment was investigated similarly.

To examine possible variations in relative risk with age and calendar time, a categorized version of age in five-year bands, and categorical quinquennia, were used instead of the one-degree-of-freedom terms, integral age and mid-year of quinquennia. This allowed an exploratory analysis of interaction, and avoided the assumption that log odds ratios per unit increase in exposure would vary linearly with age or calendar time. If fitted odds ratios within categories showed evidence of trends, their significance was tested using one-degree-of-freedom tests. Interactions were investigated for four causes of death only: lung, stomach, oesophageal and prostate cancer.

Conditional logistic analyses were carried out using the PECAN program (Storer, 1984).

3.5.3 Interpretation of regression coefficients

Both the person-years and case-referent analyses assume an exponential form for the relative risk of cause-specific mortality. Thus, regression coefficients β of exposure variables x quantify increases in log death rates per unit increase in exposure. In results sections below, the quantities $\exp(\beta)$ are quoted, and are described as relative risks per unit increase in exposure (or briefly, per WLM). They represent the multiplicative change in death rate associated with an increase of 1 WLM radon (or thoron) daughter exposure.

3.5.4 Effects of errors in exposure upon estimates of relative risk

Assuming that seam mean levels of radioactivity do not vary substantially over time, errors in the present exposure estimates can arise from four main sources:

(i) sampling error in estimates of seam means;

(ii) inter-subject variation in exposure, due to spatial and temporal variation within seams;

(iii) errors of measurement in times worked, due to inaccuracies in the Attendance Records System, or errors in recall;

(iv) assignment of colliery mean radioactivity levels to times worked in seams without measurements, in mobile 'All-Seam' jobs, and in underground jobs worked during ISP0, or at non-PFR collieries.

The analysis of this Section is confined to the effects of (i) and (ii), and in a further simplification, has been carried out assuming that the colliery mean adequately summarizes underground radioactivity levels. Although differences between seams in radon and thoron daughter levels were statistically significant, in general they were small compared to colliery differences, with the notable exception of the Waterloo Seam at Colliery Q. Under these circumstances, a model of 'constant colliery means' should provide an adequate guide to the effects of errors (i) and (ii) upon relative risk estimates.

Although there were no data on the probable magnitude of errors of type (iii), the method of the present Section was adapted to provide a guide to their effects upon risk estimates, for a range of arbitrary input values. Given its speculative nature, the analysis is outlined as part of a discussion of the effects of errors in exposure, in Section 5.3.2. Consideration of errors of type (iv) is also deferred to that Section.

Pepe *et al* (1989) discussed the estimation of relative risk parameters, when covariates are subject to error. Their approach was a development of earlier work of Prentice (1982), who showed that, from a hazard function of the form

$$\lambda_0(t)\ \exp(\beta z(t))$$

where $\lambda_0(t)$ represents a 'baseline' hazard function and z(t) a vector of covariates assumed to be without measurement error, another hazard function of the form

$$\lambda_0(t)E\left\{\exp(\beta z(t))\,\middle|\,x(t),\ \text{survival to time } t\right\}$$

could be 'induced', where x(t) denotes a measurement of z(t), subject to error. In this expression, the expectation is over subjects in the possibly hypothetical population supposed to underlie the study group, who have survived to time t and who share a measured covariate value of x(t). Prentice noted that since the joint distribution of x and z at time t would depend on survival, the induced relative risk function, namely

$$E\left[\exp(\beta z(t))\,\middle|\,x(t),\ \text{survival to time } t\right]$$

would depend on $\lambda_0(t)$ as well as β. To allow construction of a partial likelihood, Pepe *et al* suggested estimating the conditional mean and variance of z(t) given x(t) ($\mu(t,x)$ and σ^2 (t,x), say), and substituting these functions in the induced relative risk function. For example, in the case of an exponential relative risk, and a Normal distribution of a single covariate z conditional on x at time t, the induced relative risk would take the form

$$\exp\left\{\beta\mu(t,x) + \tfrac{1}{2}\beta^2\sigma^2(t,x)\right\}$$

as quoted by Pepe *et al*. The analysis given below is based on the application of this suggestion to the person-years approach.

The statistical model underlying the present application of the person-years-at-risk method specifies that the death rate y is related to true

radon daughter exposure z, according to

$$E(y|z, \text{stratum } j) = \exp(\alpha_j + \beta z)$$

where the stratum j is determined by age, calendar time, colliery and smoking habit. An 'induced' model relating death rate to estimated exposure x is obtained by noting that

$$E(y|x, \text{stratum } j) = E(E(y|x,z, \text{stratum } j)).$$

The outer expectation is over subjects in the underlying population with estimated exposure x and covariates corresponding to stratum j.

Following Prentice (1982), it is assumed that x is uninformative for y, given z, in which case

$$\begin{aligned} E(E(y|x,z, \text{stratum } j)) &= E(E(y|z, \text{stratum } j)) \\ &= E(\exp(\alpha_j + \beta z)|x, \text{stratum } j) \\ &= \exp(\alpha_j)E(\exp(\beta z)|x, \text{stratum } j) \end{aligned}$$

Further, if the distribution of z conditional on x within stratum j is Normal with mean $\mu_j(x)$ and variance $\sigma_j^2(x)$, the induced regression function takes the form

$$\exp\left[\ \alpha_j + \beta\mu_j(x) + \tfrac{1}{2}\beta^2\sigma_j^2(x)\ \right].$$

In the case where $\sigma_j^2(x)$ is independent of x, the induced regression upon x reduces to a form similar to that of the regression upon z, since the term $\frac{1}{2}\beta^2\sigma_j^2$ may be absorbed into α_j, i.e.

$$E(y|x, \text{stratum } j) = \exp\ (\alpha_j' + \beta\mu_j(x)). \qquad (1)$$

Expressions for the mean vector and variance matrix of the joint distribution of x and z, within strata, lead to estimates of the $\mu_j(x)$, given the additional assumption of Normality, as follows. Considering estimated exposures x first, these are of the form,

$$x = x_0 t_0 + x_1 t_1$$

where x_i (i = 0,1) are estimated radioactivity levels for surface and underground respectively, and t_i are estimates of time worked in these categories. The x_i are considered as random variables, and the t_i are assumed to be without measurement error.

Conditional on t_i,

$$E(x) = \mu_0 t_0 + \mu_1 t_1$$

$$Var(x) = \kappa_0^2 t_0^2 + \kappa_1^2 t_1^2,$$

where μ_i are true mean levels, and κ_0^2 are the variances of the estimates x_i.

Therefore, unconditionally,

$$E(x) = \mu_0 \tau_0 + \mu_1 \tau_1$$

$$Var(x) = \mu_0^2 \nu_0^2 + 2\mu_0 \mu_1 \nu_{01} + \mu_1^2 \nu_1^2 + \kappa_0^2(\nu_0^2 + \tau_0^2) + \kappa_1^2(\nu_1^2 + \tau_1^2),$$

where τ_i are true mean times worked in the underlying population, ν_i^2 are the corresponding variances, and ν_{01} is the covariance between time worked on surface and underground.

Considering now the true exposures z, if subjects' exposure levels are described by random processes $z_i(t)$, where $E(z_i(t)) = \mu_i$ at any time t, the cumulative exposure is given by

$$z = \int_0^{t_0} z_0(s)ds + \int_0^{t_1} z_1(s)\, ds.$$

Conditional on t_i,

$$E(z) = \mu_0 t_0 + \mu_1 t_1$$

and therefore unconditionally,

$$E(z) = \mu_0 \tau_0 + \mu_1 \tau_1 .$$

The variance of z depends on the nature of the processes $z_i(t)$. For example, if values of $z_1(t)$ for some subjects showed positive autocorrelation, as would be the case for men working habitually in areas of higher than average level such as return roadways, Var(z) would tend to increase with the autocorrelation. However, the expression for the conditional mean of z given x does not involve the variance of z, which is denoted in what follows by Var(z).

Conditional on t_i, x and z are uncorrelated, so that

$$E(xz) = E(x)E(z) = (t_0\mu_0 + t_1\mu_1)^2 .$$

Unconditionally,

$$E(xz) = \mu_0^2 \left[\tau_0^2 + \nu_0^2\right] + 2\mu_0\mu_1\left[\nu_{01} + \tau_0\tau_1\right] + \mu_1^2 \left[\nu_1^2 + \tau_1^2\right]$$

and therefore,

$$Cov(x,z) = \mu_0^2 \nu_0^2 + 2\mu_0\mu_1\nu_{01} + \mu_1^2\nu_1^2 .$$

Assuming x and z have the bivariate normal distribution (within strata), it follows that

$$\mu_j(x) = E(z|x) = \frac{Cov(x,z)}{Var\ (x)}(x - E(x)) + E(z) .$$

Under the normality assumption,

$$\text{Var } (z|x) = \text{Var}(z)\left[1 - \frac{(\text{Cov}(x,z))^2}{\text{Var}(x)\text{Var}(z)}\right]$$

is independent of x, and substitution in equation (1) (re-defining α_j') yields

$$E(y|x, \text{ stratum } j) = \exp\left[\alpha_j' + \beta \frac{\text{Cov}(x,z)}{\text{Var } x} x\right]$$

$$= \exp\left[\alpha_j' + \beta' x\right], \text{ say.}$$

Thus, if $\hat{\beta}'$ is the estimate of relative risk obtained from analysis of y in relation to estimated exposure x, an estimate of relative risk in relation to true exposure z is given by

$$\hat{\beta} = \frac{\text{Var } x}{\text{Cov } (x,z)} \hat{\beta}'$$

$$= \left[1 + \frac{\kappa_0^2(\nu_0^2 + \tau_0^2) + \kappa_1^2(\nu_1^2 + \tau_1^2)}{\mu_0^2\nu_0^2 + 2\mu_0\mu_1\nu_{01} + \mu_1^2\nu_1^2}\right]\hat{\beta}'$$

$$= k_j \hat{\beta}', \text{ say}$$

Since k_j depends on stratum, there is potentially a different estimate of β, $\hat{\beta}_j$ say, for each stratum. However, results given in Chapter 4 show that interactions between exposure and stratum variables were not statistically significant. In this case a single estimate of β can be obtained by averaging the stratum-specific $\hat{\beta}_j$ weighting inversely by var $\hat{\beta}_j = k_j^2$ Var $\hat{\beta}'$, thus:

$$\hat{\beta} = \left[\frac{\Sigma 1/k_j}{\Sigma 1/k_j^2}\right]\hat{\beta}',$$

$$\text{Var } \hat{\beta} = \left[\frac{\Sigma 1/k_j}{\Sigma 1/k_j^2}\right]^2 \text{var } \hat{\beta}'.$$

The factors k_j vary by stratum according to the dependence of the time-worked parameters τ_i, ν_i^2 and ν_{01} upon stratum variables, and also according to the variation of μ_i and κ_i^2 between collieries. Considering the latter first, μ_1 and κ_1^2 are estimated by colliery mean radioactivity level and its estimated standard error, respectively. That is, if x_m (m = 1, ..., M) denote underground measurements at a given colliery,

$$\hat{\mu}_1 = \left[\sum_{m=1}^{M} x_m \right] / M$$

$$\hat{\kappa}_1^2 = \left[\Sigma \, (x_m - \hat{\mu}_1)^2 \right] / M(M-1) .$$

Table 3.11 shows $\hat{\mu}_1$ and $\hat{\kappa}_1^2$ by colliery, for both radon and thoron daughters. Surface levels μ_0 were assumed constant over collieries - 0.54 mWL and 0.36 mWL for radon and thoron daughters respectively. The quantities κ_0^2 were arbitrarily set at 0.1 $(mWL)^2$.

The relationships between the means, variances and covariances of t_i (i = 0,1) and stratum variables were investigated by multiple regression methods, using a 3% random sample of calendar years at risk (7079 person-years). The rather arbitrary figure of 3% was chosen to give a dataset which would provide a reliable guide to the relationships of interest, without becoming inconveniently large.

Table 3.1

Mean radon and thoron daughter levels (standard deviations in brackets) measured at 11 British collieries during the 1970s and 1980, by seam.

Colliery	Seam	Radon daughters (mWL)	Thoron daughters (mWL)	No. of measure-ments
C	Warwickshire thick coal	4.00 (3.00)	4.34 (2.93)	10
F	Seven feet	1.07 (0.67)	0.53 (0.08)	6
	Nine feet lower	0.80 (0.20)	0.73 (0.15)	3
H*	Busty	6.42 (0.41)	3.15 (0.39)	6
	Tilley	7.83 (1.50)	4.10 (0.44)	3
K	Flockton	7.60 (3.36)	5.15 (2.72)	4
	Beeston	9.42 (4.77)	3.62 (1.35)	4
P	Parrot	3.07 (1.43)	3.42 (0.69)	6
	Kailblades	3.63 (0.59)	4.30 (0.52)	3
Q	High main	20.30 (8.14)	6.87 (1.82)	50
	Waterloo	6.93 (3.15)	4.33 (1.55)	3
T	Harvey (Towneley)	5.14 (1.16)	3.42 (0.65)	5
	Busty	8.67 (2.34)	3.63 (1.19)	3
V	Meadow vein	0.80 (0.85)	0.97 (0.68)	3
	Old coal	2.05 (1.36)	1.15 (0.51)	11
	Big vein	3.00 (0.75)	2.43 (0.49)	3
W	Big vein	1.45 (0.63)	1.55 (0.28)	6
X	Dunsil	0.62 (0.66)	2.97 (0.59)	4
	Beamshaw	2.50 (0.71)	4.05 (1.48)	2
	Meltonfield	0.70 (0.96)	2.53 (0.47)	3
Y	Low main	5.90 (4.38)	2.30 (0.85)	2
	Yard	5.22 (2.52)	4.12 (0.92)	13

* Non-PFR colliery

Table 3.2 Analysis of variance of the natural logarithm† of radon daughter levels (mWL).

Source of variation	df	MS
Colliery	10	16.20***
+ Seam (within colliery)	11	1.08***
Residual	131	0.26
Total ‡	152	1.36

*** $P < 0.001$

† Actually, $\log_e$ (Rn + 0.3 mWL), since a value of −0.2 mWL was recorded as data.

‡ Three of the 161 measurements were in a surface workshop. A further five underground measurements were not specific to a seam.

Table 3.3 Analysis of variance of the natural logarithm† of thoron daughter levels (mWL).

Source of variation	df	MS
Colliery	9	5.574***
+ Seam (within colliery)	11	0.289***
Residual	131	0.088
Total ‡	152	0.463

*** $P < 0.001$

† Log_e (Tn + 0.3 mWL) was used, in agreement with the transformation used for radon daughter levels.

‡ See footnote to Table 3.2.

Table 3.4 Risk categories, by colliery, with alpha-numeric codes, numbers of Occupational Groups (OGs) per category, and assigned mean levels of radon and thoron daughters (mWL) and numbers of measurements on which the means are based.

Colliery	Risk category	OGs	radon	thoron	Number of measure-ments
C	Unknown (U)	15	-	-	
	Surface (SU)	16	0.54	0.36	
	*Warwickshire Thick Coal (W)	349	4.00	4.34	10
F	Unknown (U)	24	-	-	
	Surface (SU)	19	0.54	0.36	
	All seams (A)	11	0.98	0.60	
	Six feet (6)	277	0.98	0.60	
	Nine feet (9)	259	0.98	0.60	
	*Seven feet (7)	56	1.07	0.53	6
	Four feet (4)	58	0.98	0.60	
	*Nine feet lower (9L)	55	0.80	0.73	3
	Pit bottom (PB)	4	0.98	0.60	
K	Unknown (U)	28	-	-	
	Surface (SU)	13	0.54	0.36	
	All seams (A)	46	8.51	4.39	
	*Flockton (F)	121	7.60	5.15	4
	*Beeston (B)	383	9.42	3.62	4
	Pit bottom (PB)	3	8.51	4.39	
P	Unknown (U)	34	-	-	
	Surface (SU)	20	0.54	0.36	
	All seams (A)	46	3.26	3.71	
	*Parrot (P)	195	3.07	3.42	6
	Splint (S)	167	3.26	3.71	
	*Kailblades (K)	162	3.63	4.30	3
	South coal (SO)	17	3.26	3.71	
	Coronation (C)	78	3.26	3.71	
	Little coal (L)	11	3.26	3.71	
	Smithy (SM)	9	3.26	3.71	
	Pit bottom (PB)	2	3.26	3.71	
Q	Unknown (U)	22	-	-	
	Surface (SU)	26	0.54	0.36	
	All seams (A)	32	19.05	6.66	
	*High main (H)	473	20.30	6.87	50
	*Waterloo (W)	13	6.93	4.33	3
	Second Waterloo (W2)	13	19.05	6.66	
	High Hazel (Ha)	75	19.05	6.66	
	Main Bright (M)	9	19.05	6.66	
	Low Bright (L)	6	19.05	6.66	
	Pit bottom (PB)	3	19.05	6.66	

Table 3.4 Continued

Colliery	Risk category	OGs	radon	thoron	Number of measure-ments
T	Unknown (U)	13	-	-	
	Surface (SU)	26	0.54	0.36	
	All seams (A)	39	6.46	3.50	
	*Harvey (Towneley) (H)	76	5.14	3.42	5
	*Busty (BU)	112	8.67	3.63	3
	Brockwell (BR)	76	6.46	3.50	
V	Unknown (U)	20	-	-	
	Surface (SU)	22	0.54	0.36	
	All seams (A)	44	2.00	1.34	
	*Meadow vein (M)	361	0.80	0.97	3
	Yard (Y)	27	2.00	1.34	
	*Old coal (O)	137	2.05	1.14	11
	*Big vein (B)	144	3.00	2.43	3
	Pit Bottom (PB)	3	2.00	1.34	
W	Unknown (U)	15	-	-	
	Surface (SU)	16	0.54	0.36	
	All seams (A)	44	1.45	1.55	
	Pumpquart (P)	44	1.45	1.55	
	*Big vein (B)	254	1.45	1.55	6
	Gras (G)	13	1.45	1.55	
X	Unknown (U)	31	-	-	
	Surface (SU)	20	0.54	0.36	
	All seams (A)	37	1.07	3.07	
	*Dunsil (D)	242	0.62	2.98	4
	*Beamshaw (B)	271	2.50	4.05	2
	Barnsley (BA)	91	1.07	3.07	
	*Meltonfield (M)	127	0.70	2.53	3
	Fenton (F)	11	1.07	3.07	
	Newhill (N)	74	1.07	3.07	
	Barnsley and Dunsil (BD)	8	1.07	3.07	
	Pit bottom (PB)	2	1.07	3.07	
Y	Unknown (U)	14	-	-	
	Surface (SU)	18	0.54	0.36	
	All seams (A)	51	5.31	3.88	
	High main (H)	168	5.31	3.88	
	Hutton (HU)	28	5.31	3.88	
	*Low main (L)	81	5.90	2.30	2
	C seam (C)	10	5.31	3.88	
	*Yard (Y)	131	5.22	4.12	13
	Maudlin (M)	35	5.31	3.88	
	Low main and Maudlin (LM)	5	5.31	3.88	

* Risk categories with measurements

Table 3.5 Times worked within Occupational Groups for a randomly selected member of the study group at colliery F.

ISP	OGSN*	Normal shifts	Overtime (hours)	Total time† worked (hours)	Risk‡ Category
1	0004	506.0	0	3795	6
	1035	230.0	35	1760	6
	1032	9.0	0	68	6
	0102	467.7	30	3538	6
2	1034	128.0	0	960	PB
	1035	425.2	11	3200	6
	1032	358.0	1	2686	6
	0211	4.0	0	30	6
	0173	9.0	0	68	6
	2019	24.0	0	180	U
	1048	27.0	0	202	4
	1045	100.0	1	751	6
3	1032	4.0		30	6
	1035	273.0		2048	6
	1041	10.0		75	9
	1056	47.1		353	PB
	2020	2.0		15	SU
	1056	610.4		4578	PB
	1057	10.0		75	PB
	0560	5.0		38	6
	1056	74.5		559	PB
4	1056	298.4		2163	PB
	1056	70.0		508	PB
	1056	53.0		384	PB
	1056	61.3		444	PB
	1056	57.1		414	PB
	1056	47.6		345	PB
	1056	32.0		232	PB
	1056	43.0		312	PB
	1056	53.8		390	PB
	1056	81.8		593	PB
5	1056	15.0		109	PB
	1056	30.2		219	PB
	1056	37.9		275	PB
	1056	49.0		355	PB
	4444	5.0		36	SU
	8888	2.0		14	U

Table 3.5 Continued

ISP	OGSN*	Normal shifts	Overtime (hours)	Total time† worked (hours)	Risk‡ Category
	1056	57.0		413	PB
	1056	45.0		326	PB
	1056	27.0		196	PB
	1056	52.0		377	PB
	1056	57.0		413	PB
	1056	47.0		341	PB
	1056	10.0		72	PB
	1056	10.0		72	PB
6	1056	49.7		360	PB
	1056	52.1		378	PB
	1056	60.1		436	PB

* Occupational Group Serial Number.

† Conversion factors from shifts to hours for ISPs 3 and 4 were 7.5 and 7.25 respectively.

‡ See Table 3.4 for full names of risk categories.

Table 3.6 Times worked in ISP0 within categories of coalmining activity, and obtained by Occupational History questionnaire, for a randomly selected member of the study group at colliery F.

Category of coalmining activity	Years worked	Time worked in hours	Risk Category
Colliery F:			
coalface, coal-getting	2.5	4350	Under-ground (research colliery)
coalface, non-coal-getting	0.3	522	Under-ground (research colliery)
Other collieries:			
surface	0.4	696	Surface (non-PFR colliery)

Table 3.7 Total times worked (1000s of hours) within risk categories, by ISP, for a randomly selected member of the study group at colliery F.

	Occupational History Time				Attendance Records time*								
	Colliery F		non-PFR collieries										
ISP	Surface	Under-ground	Surface	Under-ground	'Unknown'	Surface	All seams	'6'	'9'	'7'	'4'	'9L'	'PB'
0		4.87	0.70										
1								9.16					
2					0.18			6.73			0.20		0.96
3						0.01		2.12	0.07				5.56
4													5.79
5					0.01	0.04							3.17
6													1.17

* Full names of risk categories are given in Table 3.4.

Table 3.8 Cumulative exposures to radon and thoron daughters (WL hours), by ISP, for a randomly selected member of the study group at colliery F.

ISP	Exposures within ISP		Cumulative exposures	
	Radon	Thoron	Radon	Thoron
0	5.15	3.17	5.15	3.17
1	8.98	5.50	14.13	8.67
2	7.73	4.73	21.86	13.40
3	7.60	4.65	29.46	18.05
4	5.67	3.47	35.13	21.52
5	3.13	1.92	38.26	23.44
6	1.15	0.70	39.41	24.14

Table 3.9 Mean radon daughter levels (mWL) for the counties in which the PFR collieries are situated, with numbers of measurements in brackets.

Colliery	County	County mean radon daughter level (mWL)
C	West Midlands	2.2 (94)
F	Mid Glamorgan	1.4 (15)
K	West Midlands	2.2 (94)
P	Lothian	2.1 (31)
Q	Nottinghamshire	2.2 (33)
T	Durham	3.4 (23)
V	Gwent	2.6 (20)
W	Dyfed	2.5 (10)
X	West Yorkshire	3.1 (83)
Y	Durham	3.4 (23)

Table 3.10 Start dates of follow-up, by subgroup of the study population.

Colliery	Earliest survey attended			
	PFR1		PFR2	
	Singleton	Non-Singleton	Singleton	Non-Singleton
P	*Earliest Phase Two survey attended	First attendance after PFR2	Earliest Phase Two survey attended	PFR3
Q, V	†Earliest Phase Two survey attended	Second attendance in Phase One	PFR2	PFR2
Others	‡Earliest Phase Two survey attended	Second attendance in Phase One	Earliest Phase Two survey attended	PFR3

* Three of these men, exceptionally, had their time worked in Phase One estimated from a Phase Two Occupational History.

† One man had his time worked in Phase One estimated from a Phase Two Occupational History.

‡ Attendance records in Phase One were computerized for one man.

Table 3.11 Colliery mean radon and thoron daughter levels (mWL), with estimated variances of these estimates.

Colliery (No. of measure-ments)	Radon daughters		Thoron daughters	
	Estimated mean	Variance of the estimate	Estimated mean	Variance of the estimate
C (10)	4.00	0.900	4.34	0.858
F (9)	0.98	0.035	0.60	0.002
K (8)	8.51	1.940	4.39	0.578
P (9)	3.26	0.160	3.71	0.062
Q (55)	19.05	1.398	6.66	0.071
T (8)	6.46	0.708	3.50	0.082
V (17)	2.00	0.104	1.34	0.031
W (6)	1.45	0.066	1.55	0.013
X (9)	1.07	0.125	3.07	0.090
Y (15)	5.31	0.461	3.88	0.079

4. RESULTS

4.1 Vital Status

The first searches in NHSCR for attenders at PFR1 were carried out in 1970, and for attenders at PFR2, in 1988. By August 1990 there remained a group of 774 men (4.0% of the study population) whose vital status was unknown, or uncertain. No trace in NHSCR had been found of 541 men; 138 men had emigrated; for 72 men, a date of death obtained from colliery sources had not been confirmed by OPCS; and 23 men were the subject of ongoing inquiries.

Of the 613 men (541 + 72) either untraced or with an unconfirmed date of death, letters for forwarding were sent to the DSS for 612. (One man was omitted in error.) Because of insufficient, or absent, identifying information at DSS, 297 letters could not be forwarded; to the 172 which were, 118 replies were received. Of these, 113 were from the men who status was being sought. DSS also confirmed that 143 of the 612 men had died, and supplied dates of death for all but 17 of them.

As a result of this exercise, updated identifying information for the 113 men found to be alive was sent to OPCS in April 1991; dates of death for 126 decedents (143–17) were sent in June 1991.

As discussed above in Section 3.1, attempts are currently being made to reduce further the number of men of unknown vital analysis, using the records of the British Coal Corporation Pension Scheme. No results are yet available.

By the end of April 1991, when computer files of mortality information were 'frozen' for statistical analysis, 762 men were of unknown or uncertain vital status, according to OPCS. (Routine inquiries, and searches for individual men, had reduced the number from 774 during the interim). One hundred and thirteen of these men were then formally assumed to be alive as a result of DSS tracing, leaving a group of 649, made up as follows: 139 embarkees, 430 untraced in NHSCR, 56 with an unconfirmed date of death, and 24 the

subject of continuing inquiry. These men made up 3.3% of the study population, and they were excluded from statistical analysis.

4.2 Exclusions from Statistical Analysis on grounds of Missing or Unreliable Data

As discussed in the preceding section, 649 of the 19418 men for whom searches were made in NHSCR were excluded from statistical analysis, on grounds of unknown vital status. Of the remainder, five men whose reported dates of death apparently preceded their final PFR attendance were excluded. Another man was excluded, whose information on time worked during Phase One was obtained by questionnaire at a Phase Two survey, but who had no record of attendance during Phase Two. Mortality data suitable for analysis were therefore available for 18763 men.

Of the 19418 men who attended PFR1 or 2, smoking data were available for 14417. Any men who reported being a non-smoker at a PFR survey, having previously reported being an ex- or current smoker, were excluded. Two hundred and seventy-two such exclusions left a group of 14145 men with valid data.

Fifteen thousand, three hundred and twelve attenders at PFR1 and 2 had information on time worked. Exclusions from this group were as follows: 222 men who had worked at least 10000 hours in risk categories with no assigned exposure level; 127 men with no record of time worked during any of ISPs 0, 1 or 2; seven men whose recorded time worked during any ISP exceeded one half of the duration of the ISP (i.e. they had apparently been working, on average, 12 hours per day, every day, during the ISP). A group of 14956 men with valid data on time worked remained after these exclusions.

The set of men with valid data on vital status, and smoking, and time worked in risk categories with assigned exposure levels, numbered 12398. Further cross-checks, between types of data, excluded 37 more men. Fourteen had impossibly large times worked in ISP0 - their estimated ages at start of

mining were apparently under 7 years; nineteen men had attended a PFR survey, but had no record of time worked in either the ISP preceding or following; and finally, the reported date of death for four men preceded a PFR survey at which they had apparently provided information on smoking habit. Following this final step, 12361 men had data suitable for analysis.

4.3 Data Descriptions

4.3.1 Dates of entry; Ages at entry

Each man in the study entered the risk period at a PFR survey. The numbers of men entering at PFR2, 3 and 4 were, respectively 9547 (77.23%), 2427 (19.63%) and 99 (0.80%). Two hundred and eighty-two (2.28%) entered at PFR5, or at Follow-up survey if they had left the industry, and six men (0.05%) entered at PFR6 or Follow-up survey. Table 4.1 gives the distribution by colliery. For the 387 men entering during Phase Two of the PFR, information on time worked in Phase One was estimated from a Phase Two Occupational History.

The median age at entry was 44, ranging from a median of 38 at colliery Q, to a median of 50, at colliery C. The age distribution (minimum age, lower quartile, upper quartile, maximum = 15, 34, 53 and 87 respectively, see Figure 4.1) shows approximately 100 men entering the study after their 65th birthday. For these men, the risk period began at Follow-up Survey, which they attended after leaving the coalmining industry.

The most populous colliery was Y, with 1447 men participating; the least populous, W, with 654 men. The total number of men at risk during the study period increased from approximately 1700 in 1959 to 11000 in 1968, and had declined to 6500 by the start of 1989 (Figure 4.2). The 'kink' in the figure corresponds to the period between May 1962 and February 1964 when no men were entering the study (see Table 4.1).

4.3.2 Smoking

The proportion of non-smokers (i.e. men who did not smoke, and had never smoked) at each of PFR2 to 6 was roughly constant, at between 12% and 14% (Table 4.2). The proportion of ex-smokers increased from 6% at PFR2 to 22% at PFR6, and it appears that the new ex-smokers were recruited mainly from men smoking 6-10 cigarettes per day, and, to a lesser extent, 11-20 per day. However, a comparison of the numbers of men in Table 4.2 with numbers of men at risk at the same dates (Figure 4.2) shows that those giving information on smoking habits formed only a minority of the alive and at-risk cohort at PFR4, 5 and 6. Thus, the results of Table 4.2 may not provide a reliable description of the evolution of the cohort's smoking habit with time. In particular, it is possible that smokers leaving the mining industry increased their consumption, since the restriction on smoking during working hours would have been removed. Table 4.3 shows equivalent data for 2942 men who attended PFR2, 3, 4 and 5. The same patterns are evident, with the trends being slightly less marked.

4.3.3 Exposures to radon and thoron daughters

Mean estimated cumulative exposures to radon and thoron daughters, to end dates of ISPs (or dates of death, for men who died during ISPs), are shown in Table 4.4, by ISP (0 to 7). These average values are very low. For example, 3832 men who were still working in the research collieries during ISP5, which was the latest ISP for which the Attendance Records System was maintained at all 10 collieries, had an estimated mean cumulative exposure to radon daughters at that time (1978-80), of 268 WL hour (1.58 WLM), and an average thoron daughter exposure of 167 WL hour (0.98 WLM). This level of radon daughter exposure would be gained indoors, over approximately 16 years at a radon concentration of 20 Bq m^{-3}, assuming an equilibrium factor of 0.5 and 70% occupancy. Twenty Bq m^{-3} is close to the average indoor level reported by NRPB in a recent survey of 2000 British homes (Wrixon *et al*, 1988). Although average exposures were low, there was considerable variation in the individual values. Boxplots, summarising the distributions of cumulative exposures to end-dates of ISPs (Figures 4.3 and 4.4) showed

markedly skewed distributions for all ISPs, except 7. For ISPs 1 to 6 the upper quarter of the distributions of radon daughter exposure ranged from 200–300 WL hour to 1500–1800 WL hour. For thoron daughters, the range was 150–250 WL hour to 500–650 WL hour. (The 'box' in these plots indicates quartiles and median; lines above and below the box extend to the upper and lower 5% points. Individual data points in the tails of the distribution are shown by dots; in Figures 4.3, 4.4, 4.7 and 4.8 these have merged to give continuous heavy lines.)

The distributions of total cumulative exposure to radon and thoron daughters for all 12361 members of the study group (i.e. cumulative exposure to the end–date of the latest ISP in which time was worked, or to date of death) showed, as expected, the long tails already seen in the boxplots of ISP–specific exposures (Figures 4.5 and 4.6). However, when the same exposures were viewed by colliery (Figures 4.7 and 4.8) the skewness disappeared. These boxplots also illustrate the large differences between collieries in total cumulative exposure.

4.3.4 Radioactivity surveys

Radon daughter levels measured at collieries C and Y during the 1990 surveys are given in Table 4.5 The average of 24 measurements made in 1990 at colliery Y was 7.4 mWL (s.d. of 6.2 mWL), which is close to the mean 1978/79 level (over 15 measurements) of 5.3 mWL (s.d. 2.6). Two measurements made in 1983 and 1986 in the upcast airstream were somewhat higher (16.2 and 12.0 mWL). At colliery C, 26 measurements were made in the 1990 survey. The average radon daughter level was 18.5 mWL (s.d. 7.5), which is considerably higher than the mean level of 4.0 mWL (s.d. 3.0, 10 measurements) measured in 1976/77. The difference is statistically significant, and remains so after adjustment for the effect of ventilation distance, which was twice as great, on average, in the later survey. Adjustment reduces the ratio of geometric means between the two surveys from 5.8 to 4.8, which still represents a substantial increase. (The positive correlation between ventilation distance – the distance travelled by the ventilating airstream from the intake shaft to the point of measurement – and

radon daughter levels was noted by Edlin *et al* (1984).) A single measurement (2.7 mWL) was made at this colliery in 1985 in the upcast air, but unlike the upcast values at colliery Y, it was lower than either the 1979 or 1990 survey means. At collieries other than C or Y, levels measured during the 1980s were higher than 1970s levels, except at colliery Q, where the single measurement made in 1985 (16.1 mWL) was close to the 1972 mean (17.2 mWL), and rather lower than the 1979/80 mean (21.4 mWL).

Thoron daughter levels measured in 1990 at collieries C and Y (Table 4.6) were greater on average than those measured in the 1970s by factors of approximately 2 and $3\frac{1}{2}$ respectively. The differences were statistically significant.

4.3.5 Indoor exposures

Estimates of the average cumulative indoor exposure to radon daughters, calculated by the method of Section 3.2.9, are given in Table 4.7. The results suggest that the proportion of total exposure (i.e. work time exposure plus indoor exposure) acquired during working time might be expected to vary from 5% at colliery X to 50% at colliery Q. For four collieries (F, V, W and X) the proportion did not exceed 10%; Figure 4.7 shows that cumulative exposures at these collieries were very low. In general, the fact that working times were substantially less than estimated times spent indoors, was the main reason for low values of these proportions. In the calculations, 6132 hours per year (at ages over 15) were assumed to have been spent indoors. This is considerably greater than the figure of 1740 hours per year used in the calculation of working-time exposure.

4.4 External Comparisons of Mortality - All Causes of Death, and Lung Cancer

There were 5852 deaths in the study group of 12361 men with valid data, between dates of entry and the end of the study (31/12/1989). Five hundred and twenty-one of these were from lung cancer. Comparison with regional

death rates gave an all-causes SMR of 96, and a lung cancer SMR of 87 (Table 4.8). The latter was statistically significantly lower than 100; the 95% confidence interval was 80-95. All causes SMRs within ten-year age categories varied between 91 and 114, lung cancer SMRs between 80 and 111; there were no signs of any trends.

4.5 The Relationship between Radon and Thoron Daughter Exposure and Cause-Specific Death Rates

4.5.1 Lung cancer

Lagged radon daughter exposures could not be estimated for 15 of the 521 lung cancer deaths, which occurred within 10 years of the start of exposure records. Analyses were therefore based on 506 deaths. Figure 4.9 shows lung cancer death rates per 100000 person-years by radon daughter exposure category and age at death. (The data on which Figures 4.9, 4.10, 4.11 and 4.12 are based, are given in Appendix 5.) Five men under 45 died of lung cancer; rates for this age group have not been plotted. There is an indication of an increasing trend in men aged over 75, although error bars (95% confidence limits for the underlying Poisson mean) are wide, but otherwise there is no evidence of an exposure response relationship. Regression analysis of death rates upon age, smoking habit, calendar time period and colliery showed that the effects of these factors were statistically significant; results of fitting these variables in order of greatest reduction in deviance are given in Table 4.9. Of all six two-factor interactions, only that between age and calendar time was statistically significant. After allowing for these effects, differences in death rate between radon daughter exposure categories were not statistically significant (Chi square (X^2) on 6 df = 1.83, see Table 4.9). A likelihood ratio test for trend (see Section 3.5.1) was also not statistically significant (X^2 on 1 df = 0.27). The estimated relative risk per WLM was 0.98 (95% confidence limits = 0.90 to 1.06). The same test was carried out using a log transformed exposure; the result was again non-significant (X^2 on 1 df = 0.25). Furthermore, none of the interactions between the four stratifying variables and exposure, treated either as a categorical or a continuous variable was statistically significant.

Likelihood ratio statistics for continuous exposure, both untransformed and logged, were as follows:

		Chi-square	
Variable	df	Untransformed exposure	Ln (exposure)
Age	5	9.14	10.54 (0.05<P<0.1)
Smoking habit	5	5.84	7.55
Colliery	9	12.35	8.44
Calendar time	2	3.14	0.84

Differences in trends between age groups approached significance in the analysis of log exposure; the largest t-statistic testing differences from age group 'younger than 35', was -0.41, and occurred for age group 55-64, where death rates declined with increasing exposure (see Figure 4.9). Death rates estimated by the statistical model of Table 4.9, show the effects of age and smoking (see Table 4.10). The lack of any trend with exposure is clear.

The results of a comparison of men who died from lung cancer (cases) to men still alive at the same age (referents) are shown in Table 4.11. Thirteen cases could not be matched, leaving 493 cases for analysis. The average case-referent difference was negligible (-1 WL hour), and differences within age and calendar time groups were small compared to standard errors, with no evidence of any trends. Differences within collieries were also unremarkable, the only statistically significant result occurring at colliery Y, where cases had 35 WL hour more exposure than referents ('t' on 68 df = 2.24). Non-smoking cases, and cases who smoked fewer than 10 cigarettes per day, had higher exposures than referents: the difference for smokers of 6-10 cigarettes daily (54 WL hour) was 2.9 times its standard error. In the higher smoking categories, and in pipe and ex-smokers, the sign of the difference was reversed. Table 4.12 shows results of conditional logistic regression analysis. The effect of radon daughter exposure overall was not statistically significant. There was also no indication of a varying effect by age, calendar time, or colliery. However there was evidence of a differential effect of exposure by smoking category ($P < 0.05$). Fitted relative risk

parameters (Table 4.13) showed a slight tendency to increase with age, but a test for trend was not statistically significant. The apparent decreasing trend with calendar time was also non-significant. Relative risks were raised for non- and light smokers (i.e. fewer than 10 per day), but only significantly so for smokers of 6-10 per day. In higher smoking categories, increased radon daughter exposure was apparently associated with a reduced risk of lung cancer mortality, relative to lower exposure.

Lung cancer death rates per 100000 person-years by thoron daughter exposure (lagged by 10 years) and age at death are shown in Figure 4.10. There was only a single person-year of observation in the highest exposure category at age 45-54, and the corresponding point has not been shown in the Figure. In the oldest and youngest age groups, rates increase with increasing exposure, but there is no indication of any trends in other groups. A regression analysis with adjustments for age, smoking calendar time and colliery identical to those of the radon analysis, showed that differences between exposure categories were not statistically significant (X^2 on 5 df = 0.50). Fitted risks by exposure category, relative to a baseline category of 0.25 WL hour, were:

WL hour	Relative risk
25-	0.92
50-	0.93
100-	0.91
200-	0.96
400-	1.05

A test for trend was not statistically significant (X^2 on 1 df = 0.27); the estimated relative risk per WLM was 1.05 (95% limits, 0.88-1.26). The same test, using logged exposure, was likewise not statistically significant (X^2 on 1 df = 0.01). Interactions between exposure (treated either as categorical or continuous) and the four stratifying variables were also not statistically significant. Likelihood ratio statistics for continuous exposure, both untransformed and logged, were as follows:

Variable	df	Chi-square: Untransformed exposure	Chi-square: Ln (exposure)
Age	5	7.12	7.38
Smoking habit	5	6.19	8.30
Colliery	9	16.24 (0.05<P<0.1)	11.90
Calendar time	2	0.28	0.02

Colliery differences approached significance; relative risks varied from 0.02 per WLM at colliery W to 2.16 per WLM at colliery Y.

Lung cancer cases had slightly more exposure to thoron daughters than their matched referents (2 WL hour). There was little variation by age or calendar time, apart from a relatively large difference (37 WL hour, 't' on 30 df = 2.54) for men aged 80 years and over. Within collieries, differences were well below two standard errors, except at colliery Y, where 26 WL hour more exposure was recorded for cases ('t' on 61 df = 2.36). The variation across smoking categories showed a pattern previously observed for radon daughter exposure: positive differences for non- and 'light' smokers becoming negative in the higher smoking categories. Conditional logistic regression analysis (Table 4.14) showed that, overall, thoron daughter exposure did not have a statistically significant effect upon lung cancer death rates. There was also no evidence that relative risks varied between age groups, calendar time periods, collieries or smoking categories. Fitted relative risk parameters tended to increase with age, and decrease with calendar time, but neither of these trends was statistically significant. The pattern of variation between smoking categories was similar to that seen in the case-referent analysis of radon daughter exposure; a relative risk of 1.78 per WLM thoron daughter exposure for smokers of 6-10 cigarettes daily differed significantly from unity (95% limits = 1.03 to 3.05).

Cases and referents were also compared in respect of a combined dose measure of radon and thoron daughters. The mean dose for both cases and referents was 19.7 mSv, which would represent approximately 15 years absorption of the estimated mean effective dose equivalent per year received

by the UK population from indoor and outdoor sources, according to a recent report (Wrixon *et al*, 1988). Case–referent differences within age groups, calendar time groups, and collieries were not statistically significant, except at colliery Y, where cases had absorbed 2.6 mSv more than referents ('t' on 68 df = 2.27). The pattern of differences by smoking category was, not surprisingly, similar to that observed for both exposure indices – positive differences among non– and light smokers, negative in heavier smokers. The largest difference observed was for non–smokers (7.4 mSv); but only the difference for smokers of 6–10 cigarettes per day (3.6 mSv) was statistically significant ('t' on 79 df = 2.85). Conditional logistic regression analysis (Table 4.15) showed that, overall, dose did not have a statistically significant effect upon lung cancer risk. There was also no evidence of differential effects of dose with age, calendar time period, or colliery; but the interaction with smoking habit was statistically significant (Chi square on 8 df = 17.47, $P < 0.05$). Relative risks exceeding unity were estimated for non–smokers, and smokers of 1–5 and 6–10 cigarettes per day, but only in the latter category was the risk significantly raised (1.36, 95% confidence interval 1.04–1.77).

Tables of results for thoron daughter exposure and the combined measure of dose, similar to 4.11 and 4.13, are reported elsewhere (Maclaren, 1992).

To examine goodness–of–fit of log linear regression models fitted to tables of death rates (see Table 4.9 for structure of models used for both exposures), predicted numbers of deaths were tabulated by age and exposure, and divided by tabulated person–years to give predicted death rates. These were then plotted, together with observed death rates. Predicted rates by radon daughter exposure (shown by bold lower case e's – for 'expected' – in Figure 4.11) all lay within 95% confidence limits based on the observed death rates (shown by O's), with one exception (age group 75+, exposure group 400–799 WL hour). For thoron daughters, all predictions lay within the confidence limits (Figure 4.12). Examination of deviance residuals from both regression analyses showed that one cell of each of the person–years tables had generated a single large standardized residual: 4.18 for radon, 3.75 for thoron. When analyses were repeated omitting these cells, results were virtually unchanged.

Effects upon relative risk estimates of applying various lags to cumulative exposures were also examined in person-years analyses. Periods of 5, 15 and 20 years were considered; and only the main effects of lagged radon and thoron daughter exposures were tested. (Recall that a period of 10 years had been used in the main analysis.) Risks of lung cancer mortality relative to a baseline exposure category of 0-25 WL hour, adjusted for the effects of age, calendar time, colliery and smoking habit according to the model shown in Table 4.9 did not differ significantly from unity, for either exposure, and for all lags considered (Tables 4.16 and 4.17).

Finally, a person-years analysis was carried out of data from colliery Q, where radioactivity levels were highest; results are given in detail in Appendix 6. Allowing for the effects of age, smoking and calendar time, relative risks per WLM exposure were estimated to be 0.96 (radon) and 0.94 (thoron). Interactions with stratifying variables were non-significant, although there was a suggestion that risks per WLM thoron daughter exposure varied with smoking habit ($0.05 < P < 0.1$). The pattern of interaction resembled that found in case-referent studies of radon daughter exposure and the combined dose measure.

4.5.2 Stomach cancer

There were 219 deaths from stomach cancer; exposures could not be estimated for 18. Death rates per 100000 person-years are shown in Figure 4.13, by age and radon daughter exposure category. One man under 45 died from stomach cancer; rates for this age group have not been plotted. There are no indications of increasing trends in death rate with increasing exposure. As in the lung cancer analysis, the statistical significance of differences between exposure categories was assessed after allowing for possible effects of age, smoking habit, calendar time and colliery. The results are summarized in Table 4.18. Age and calendar time both had statistically significant effects, and there was evidence of real differences between smoking categories, which varied with calendar time (X^2 on 10 df = 19.02, $P < 0.05$). The form of this interaction is shown in Table 4.19, which gives

predicted death rates. There is little variation between smoking categories during either of the periods 1970–79 or 1980–89, but rates for non– and ex–smokers were elevated, and those for pipe smokers lowered, during 1960–69. After allowing for these effects, differences between radon daughter exposure categories could have arisen by chance (X^2 on 6 df = 9.72). Estimated death rates (Table 4.19) showed an increasing trend (with fluctuations) with increasing exposure, but a test for trend was not statistically significant (X^2 on 1 df = 0.04); relative risk per WLM = 1.01, 95% limits = 0.87 to 1.16). The same test, using log exposure, showed stronger evidence of a trend, but was still not significant (X^2 on 1 df = 2.17, $P<0.2$). Interactions between exposure and the four stratifying variables were also not significant – likelihood–ratio statistics (continuous exposure) were as follows:

		Chi-square	
Variable	df	Untransformed exposure	Ln (exposure
Age	5	2.48	3.03
Smoking habit	5	2.69	1.84
Colliery	9	14.77	12.95
Calendar time	2	4.78	1.99

Comparisons in lagged radon daughter exposure between men who died of stomach cancer (cases) and their matched referents are given in Table 4.20. Of 201 cases with estimated exposure, four could not be matched. The average difference between all cases and referents was negligible (–4 WL hour). Differences within age and calendar time strata did not show any trends, and with one exception, were not statistically significant (3 cases who died in 1960–64 had on average 46 WL hour more exposure than 23 matched referents, 't' on 2 df = 5.61, $P < 0.05$). Differences within collieries were likewise unremarkable. However, there was evidence of variation with smoking habit: cases who smoked 11–20 cigarettes per day had 37 WL hour more exposure than referents ('t' on 61 df = 2.10), and ex–smoking cases 42 WL hour more ('t' on 27 df = 2.42). Other differences were not significant, and, with one exception, negative. Logistic regression analysis (Table 4.21) showed that overall, there was no statistically significant effect of

radon daughter exposure, and no evidence of interaction with age, calendar time, colliery or smoking habit. Regression coefficients are given in Table 4.22.

Figure 4.14 shows stomach cancer death rates by lagged thoron daughter exposure and age at death; increasing trends with exposure are discernible, to some extent, in the two oldest age groups. Regression analysis, with adjustment for age, calendar time, colliery and smoking habit as in the radon analysis, showed no statistically significant differences between exposure categories (X^2 on 5 df = 4.33). Risks relative to a baseline category of 0–25 WL hour were:

Exposure (WL hour)	Relative risk
25-	0.83
50-	0.83
100-	1.04
200-	1.35
400-	0.92

A test for trend was not statistically significant (X^2 on 1 df = 1.67; relative risk per WLM = 1.22, 95% limits = 0.90 to 1.65). A non-significant result was also obtained using log exposure (X^2 on 1 df = 1.57). None of the interactions between exposures and stratifying variables was statistically significant; the Table below shows likelihood-ratio statistics, treating exposure as a continuous variable.

		Chi-square	
Variable	df	Untransformed exposure	Ln (exposure)
Age	5	0.30	2.05
Calendar time	2	2.70	1.55
Colliery	9	13.36	13.20
Smoking habit	5	2.91	1.76

Case-referent differences were examined by age, calendar time period, colliery and smoking habit. The difference over all matched sets was small (2 WL

hour), and no age group, calendar time period or colliery showed statistically significant differences. There was also no evidence of trends with time-related factors. Cases who smoked 11-20 cigarettes per day had 17 WL hour more exposure than referents ('t' on 61 df = 2.02), but differences in other smoking categories were not statistically significant. Conditional logistic regression analysis (Table 4.23) showed no statistically significant effects.

Tables of case-referent differences in thoron daughter exposure, and of estimated relative risks, are reported elsewhere (Maclaren, 1992).

Goodness-of-fit of regression models was investigated by the same method used in the analysis of lung cancer mortality. Figures 4.15 and 4.16 show predicted death rates by exposure and age; all predictions lay within 95% confidence limits corresponding to observed rates. Also, there were no unusually large standardized residuals generated in the analysis of either exposure variable, radon or thoron daughters.

4.5.3 Other causes of death

Case-referent differences in radon and thoron daughter exposure for eight other causes of death are given in Table 4.24. Exposure could not be estimated for one of the 17 cases of buccal cavity cancer, three of the 42 oesophageal cancer cases, two of the 79 prostate cancer cases, and the single case of salivary gland cancer. In addition, one of the two cases of laryngeal cancer could not be matched, and seven of the 77 cases of prostate cancer with estimated exposures.

Approximate 't' statistics are large for bone cancer, but they are not statistically significant. (The two deaths from this cause fall into two strata, and hence 't' statistics have one degree of freedom only. This highlights the fact that these simple descriptive tests make no use of within-stratum variation. In the conditional regression analyses, however, full use is made of the available information.) Otherwise, 't' statistics are all below critical values, the largest ones (negative) occurring for oesophageal cancer.

Conditional logistic regression analysis (Table 4.25) gave estimated relative risks of death from oesophageal cancer of 0.66 (95% confidence interval 0.47–0.91) per WLM radon daughter exposure, and 0.47 (0.26–0.85) per WLM thoron daughter exposure. For other causes of death, there was no evidence of any association between death rates and either exposure measure. (As in the conditional logistic regression analyses of lung cancer and stomach cancer, only the exposure measures were included in these analyses. Adjustment for the effects of age, smoking, colliery and calendar time was by matching.)

Variations in relative risk per WLM with age, calendar time and smoking category were examined for oesophageal cancer and prostate cancer. Differences in relative risk of oesophageal cancer mortality per WLM between four 10–year age categories were not statistically significant for either radon or thoron daughter exposure. However, fitted relative risk parameters showed a decreasing trend, which was significant for both exposures ($P < 0.05$). For radon daughter exposure, the estimated relative risk per WLM at age 55 was 1.40; risks declined by an estimated factor of 0.58 per 10 years of age. (One man died from this cause at age 41; the next death occurred at age 54.) The estimated relative risk per WLM thoron daughter exposure at age 55 was 3.49; risks declined by an estimated factor of 0.28 per 10 years of age. Of the three factors considered, age, calendar time, and smoking, only age was shown to influence the relative risk of oesophageal cancer mortality. Differences between five calendar time periods and four smoking categories were not statistically significant. Finally, there was no evidence that the relative risk of prostate cancer mortality varied with any of the three factors.

4.6 The Effects of Errors in Estimated Exposures upon the Relative Risk of Lung Cancer

The stratum–dependent factors k_j (see Section 3.5.4) are functions of the joint distribution of the estimated exposure x and the true exposure z, within strata. The means, variances and covariance of this distribution depend upon the means, variances and covariances of times worked on surface and

underground, on the true mean radioactivity levels on surface and underground, and on the variances of the estimates of these levels.

Relationships between two response variables – time worked on surface and time worked underground, both lagged by 10 years – and the categorical variables determining strata (age, calendar time, colliery and smoking habit) were examined in two multiple regressions. These were carried out in a three percent sample of person-years (7079 person years). Results are given in Tables 4.26 and 4.27. Only 3.3% of the variation in time worked on surface was explained by the stratum variables (main effects only), age alone accounting for 2.7%. On the other hand, 42.2% of the variation in time worked underground was explained by the stratum variables, age in this case accounting for 40.6%. These relationships are clarified in Tables 4.28 and 4.29 which show the distribution of person-years, by age at risk and time worked on surface and underground respectively (note the different categorization of time worked in the two Tables). The weakness of the regression of time worked on surface upon age is caused by high numbers of men of all ages with low times worked (i.e. less than 2000 hours).

On the basis of these results, the joint distribution of time worked on surface and underground was considered in relation to age only. Although other variables were statistically significant, their contributions to explaining the variation in times worked were relatively small. Table 4.30 shows means, variances and the covariance, by age at risk. These quantities were used as estimates of the population parameters τ_i, ν_i^2, ν_{01}, within strata (see Section 3.5.3).

Table 4.31 shows the factors k_j by colliery and age group. Considering the adjustments required to the radon daughter effect, these are smallest at Q, where the largest number of measurements were made, and largest at F and X where mean levels were lowest. Also, adjustments tend to increase with age, reflecting the increasing mean and variance of times worked, and the decreasing negative covariance. These trends are predicted by the formula for the k_j given in Section 3.5.4. The weighted average values of the k_j, appropriate when no interactions were shown between stratum variables and

exposures as in the present case, are 1.19 for radon daughters and 1.11 for thoron.

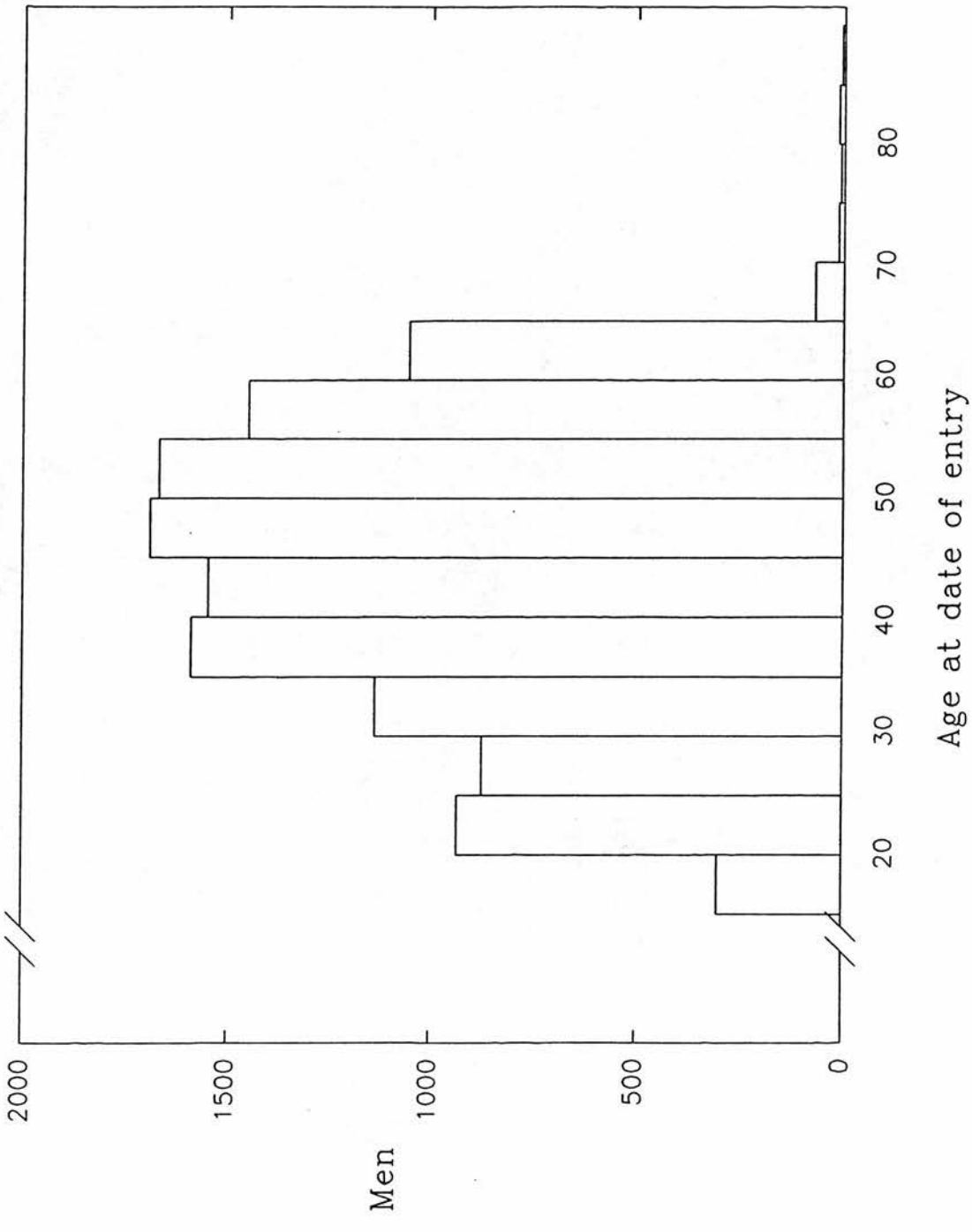

Figure 4.1 Distribution of age at date of entry to the study.

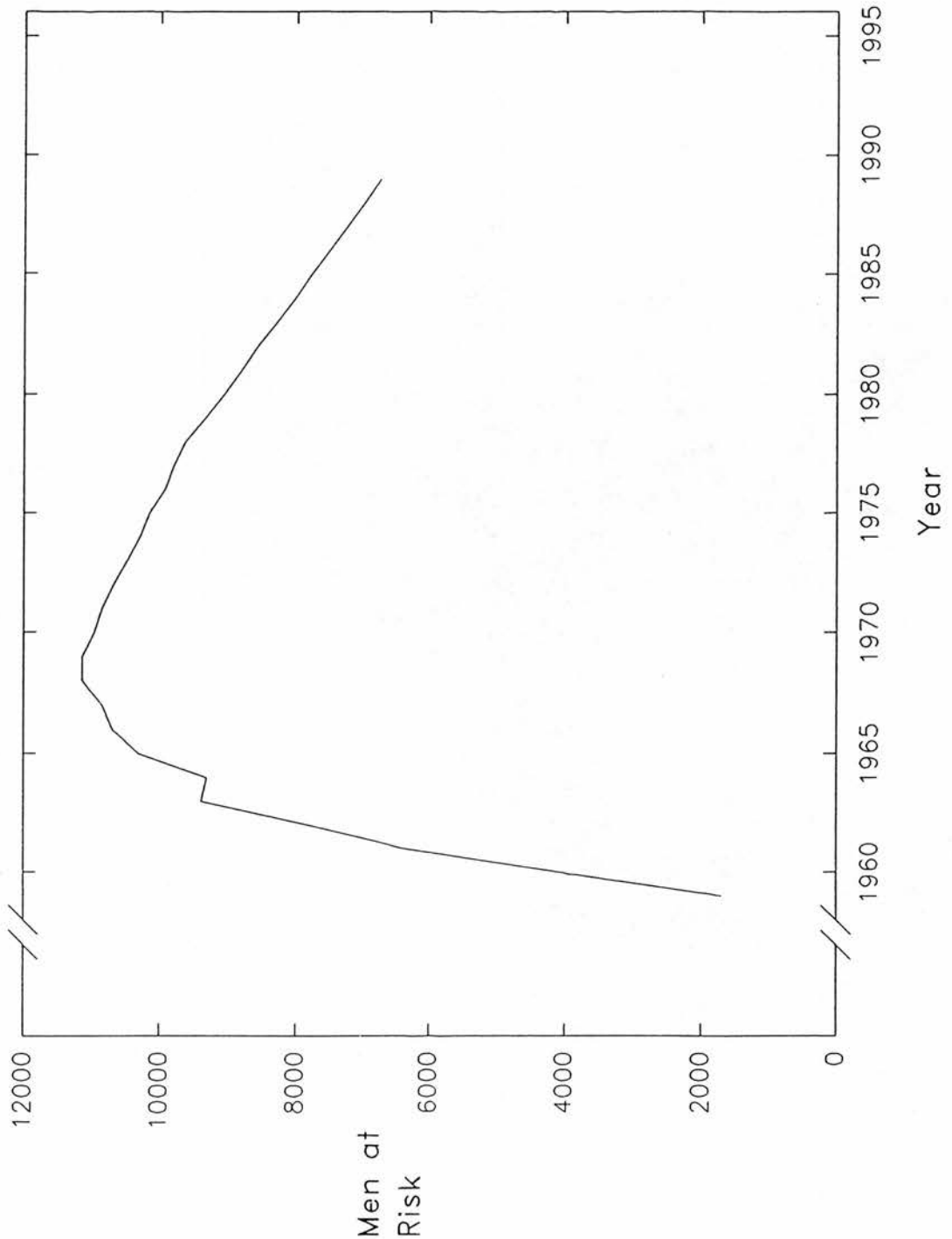

Figure 4.2 Number of men at risk by calendar year.

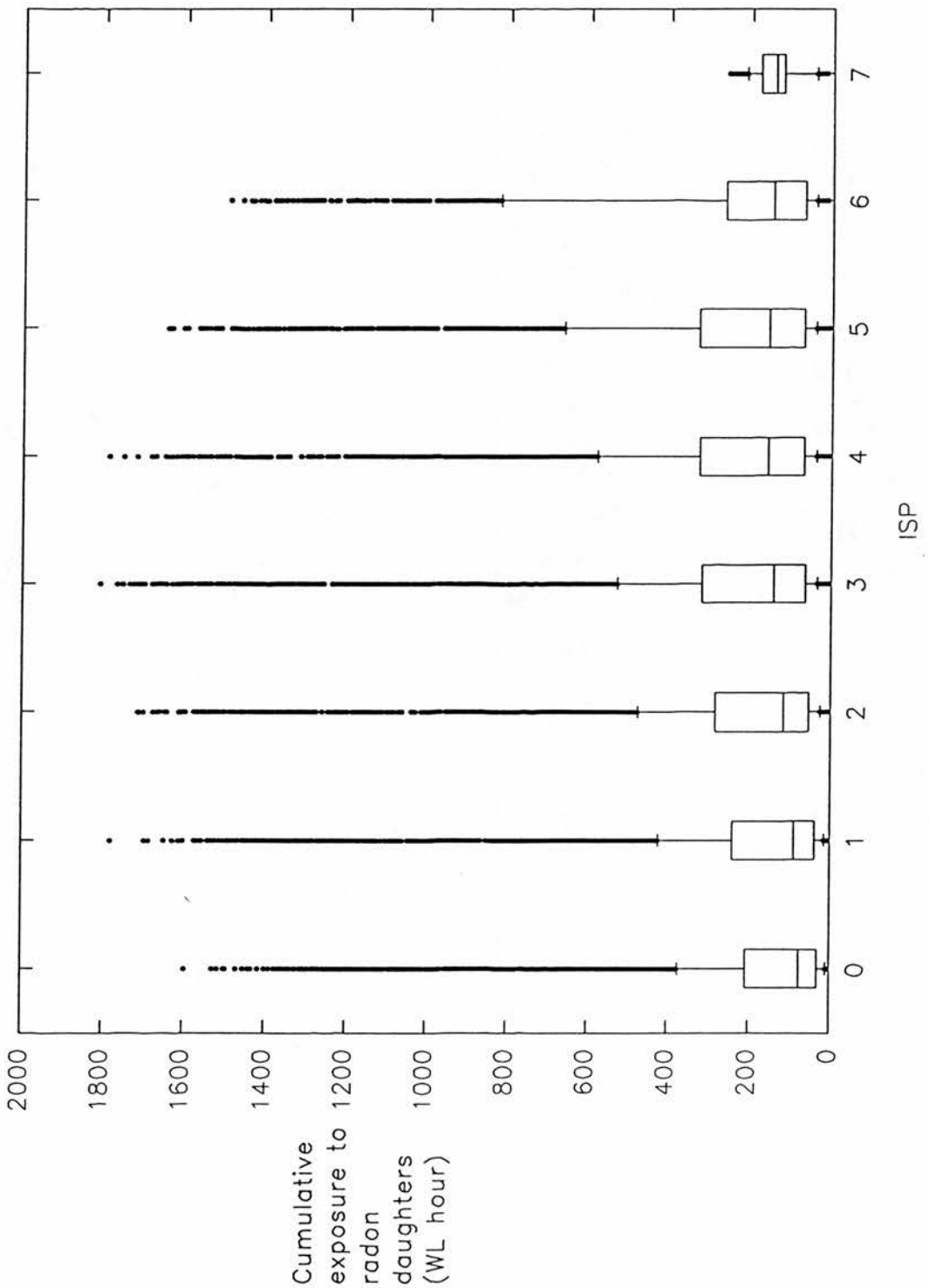

Figure 4.3 Boxplots, showing distributions of cumulative exposure to radon daughters, to ISP ends.

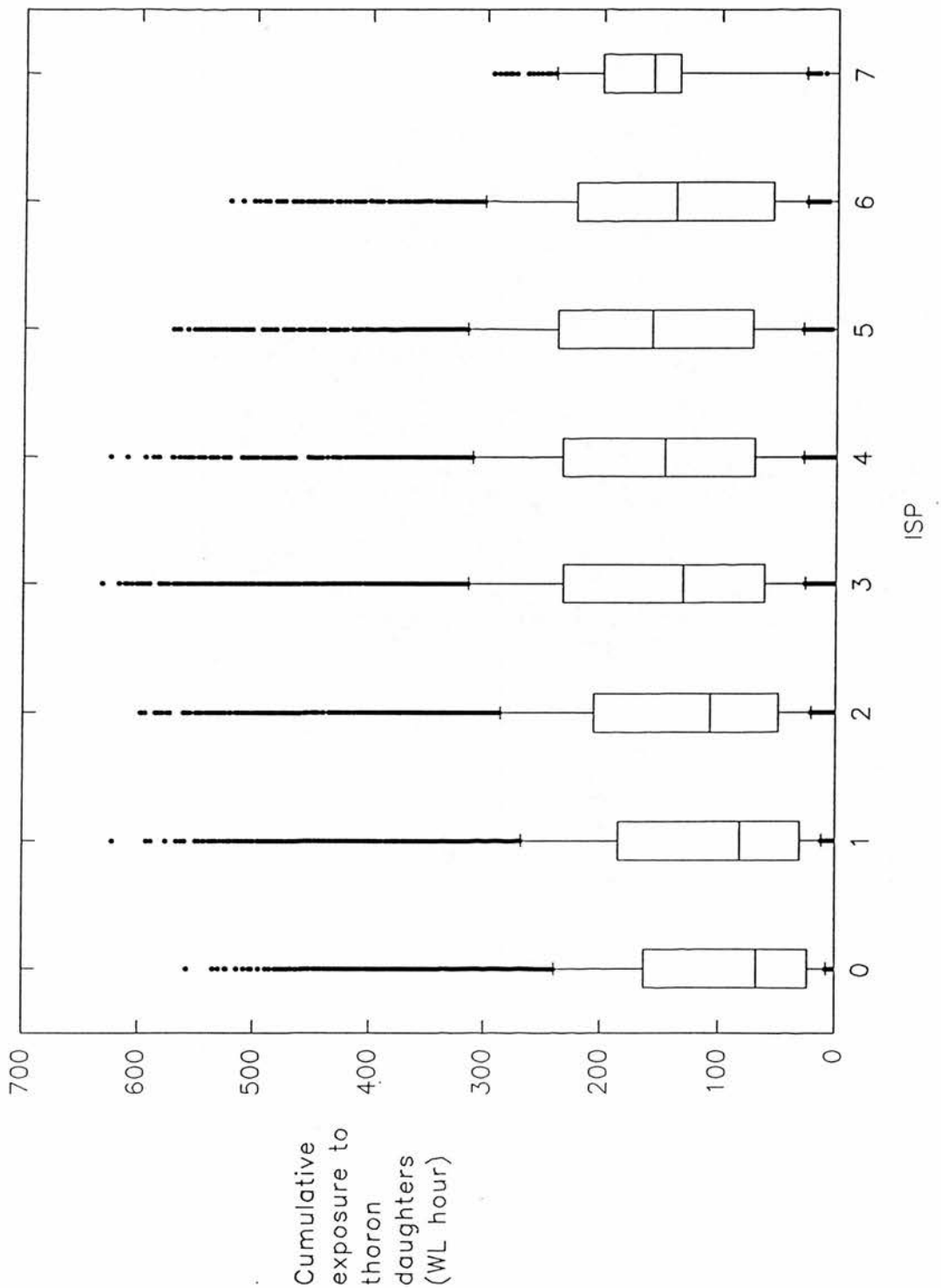

Figure 4.4 Boxplots, showing distributions of cumulative exposure to thoron daughters, to ISP ends.

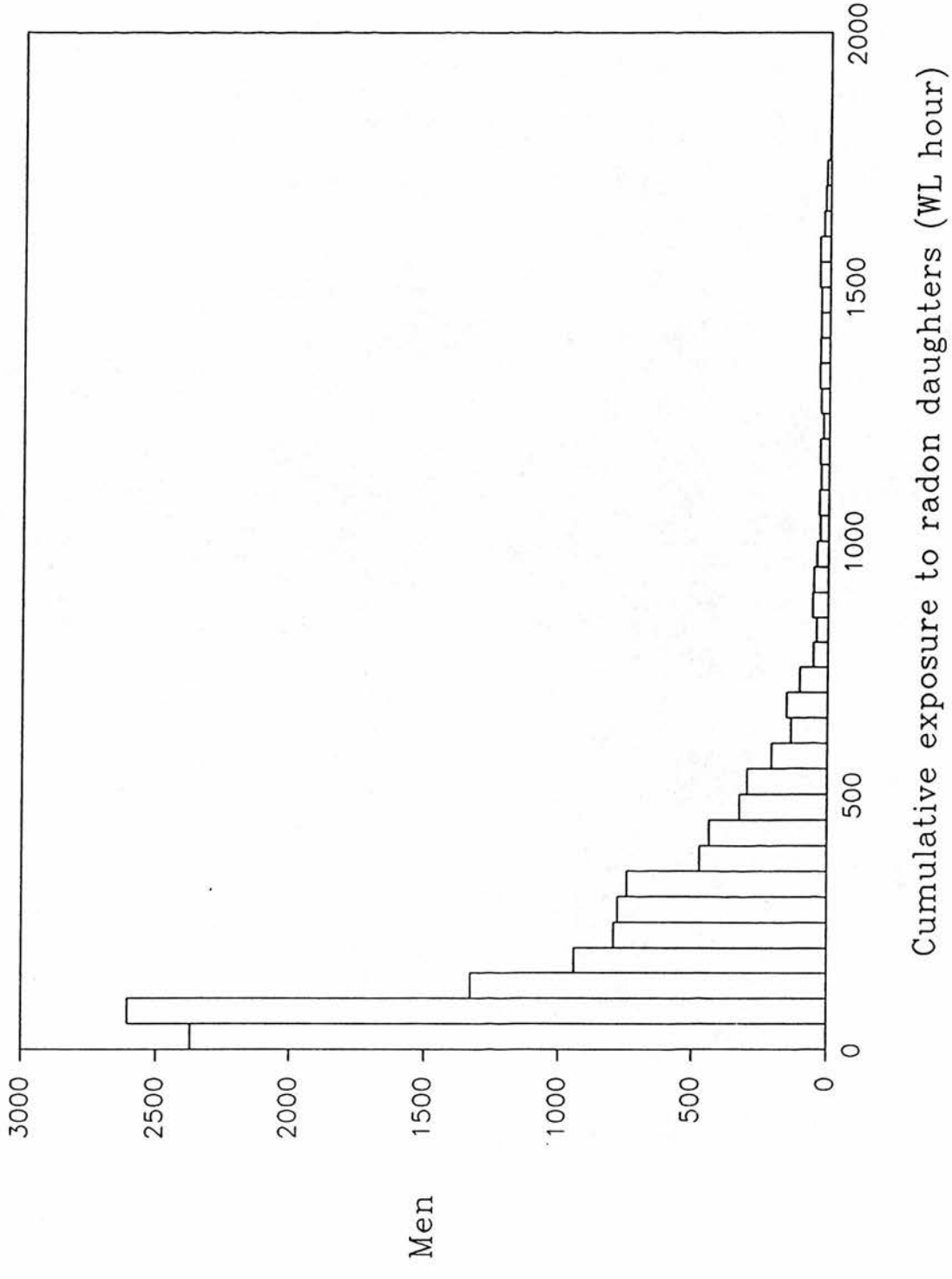

Figure 4.5 Distribution of total cumulative exposure to radon daughters.

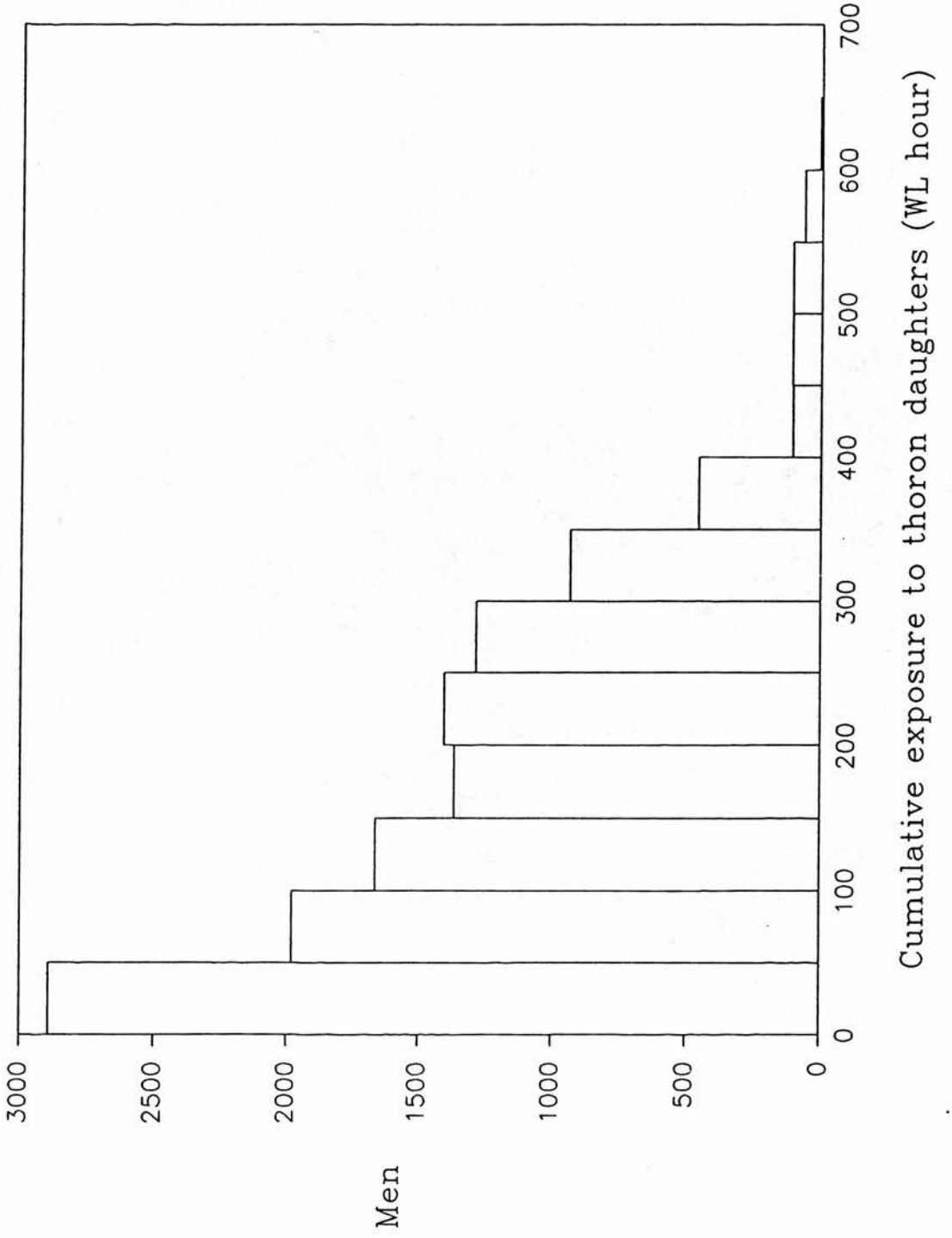

Figure 4.6 Distribution of total cumulative exposure to thoron daughters.

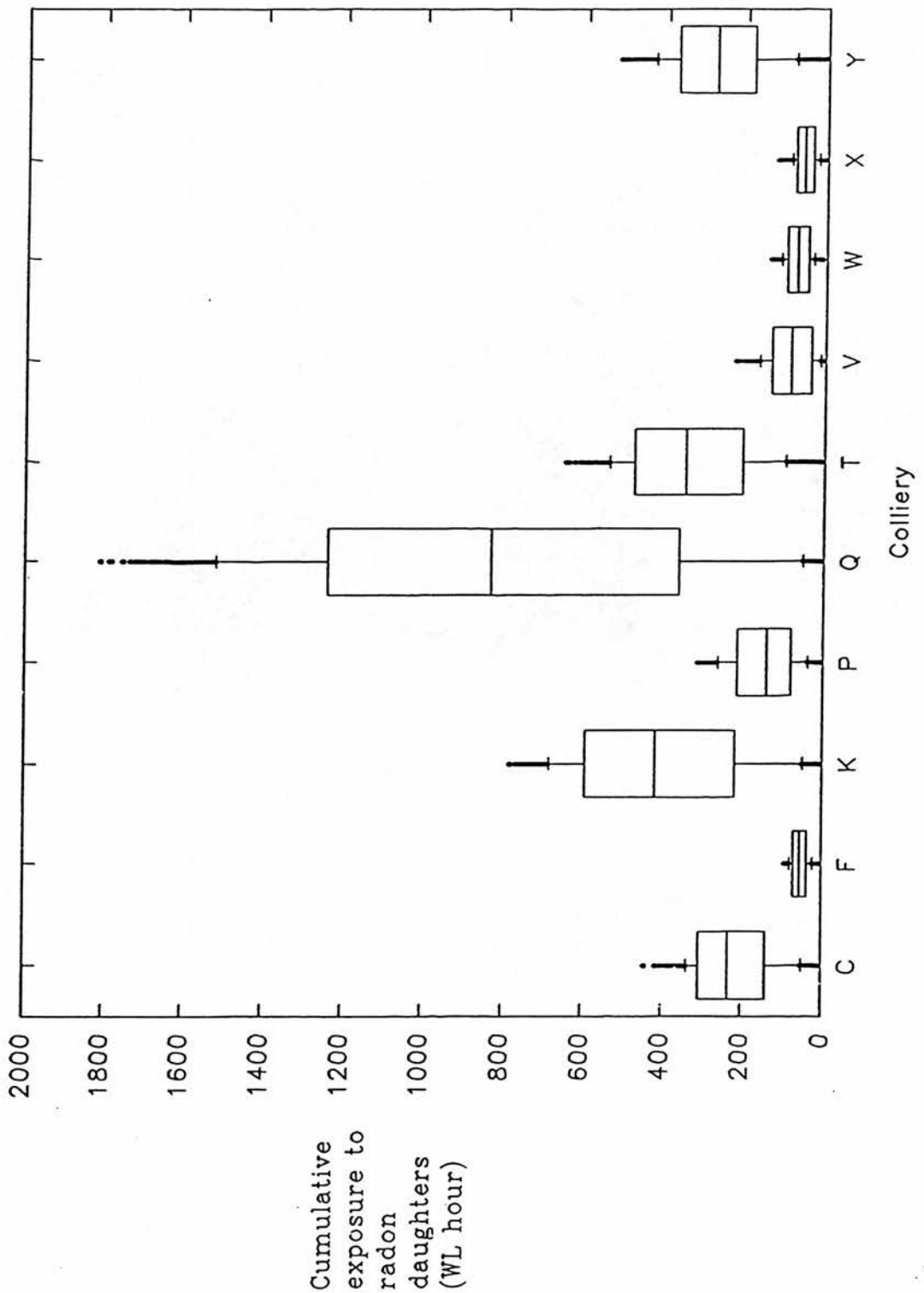

Figure 4.7 Boxplots, showing distributions of total cumulative exposure to radon daughters, by colliery.

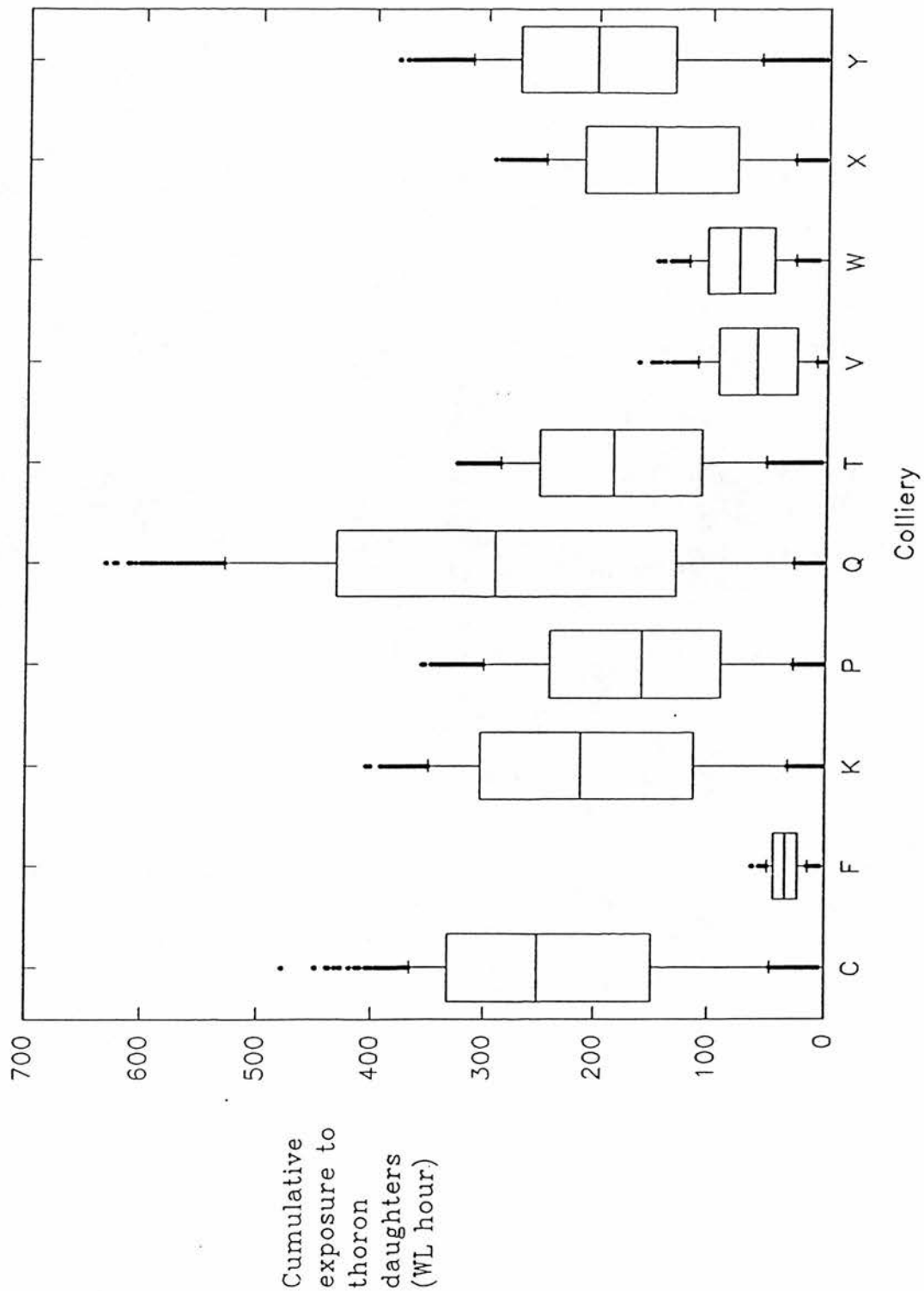

Figure 4.8 Boxplots, showing distributions of total cumulative exposure to thoron daughters, by colliery

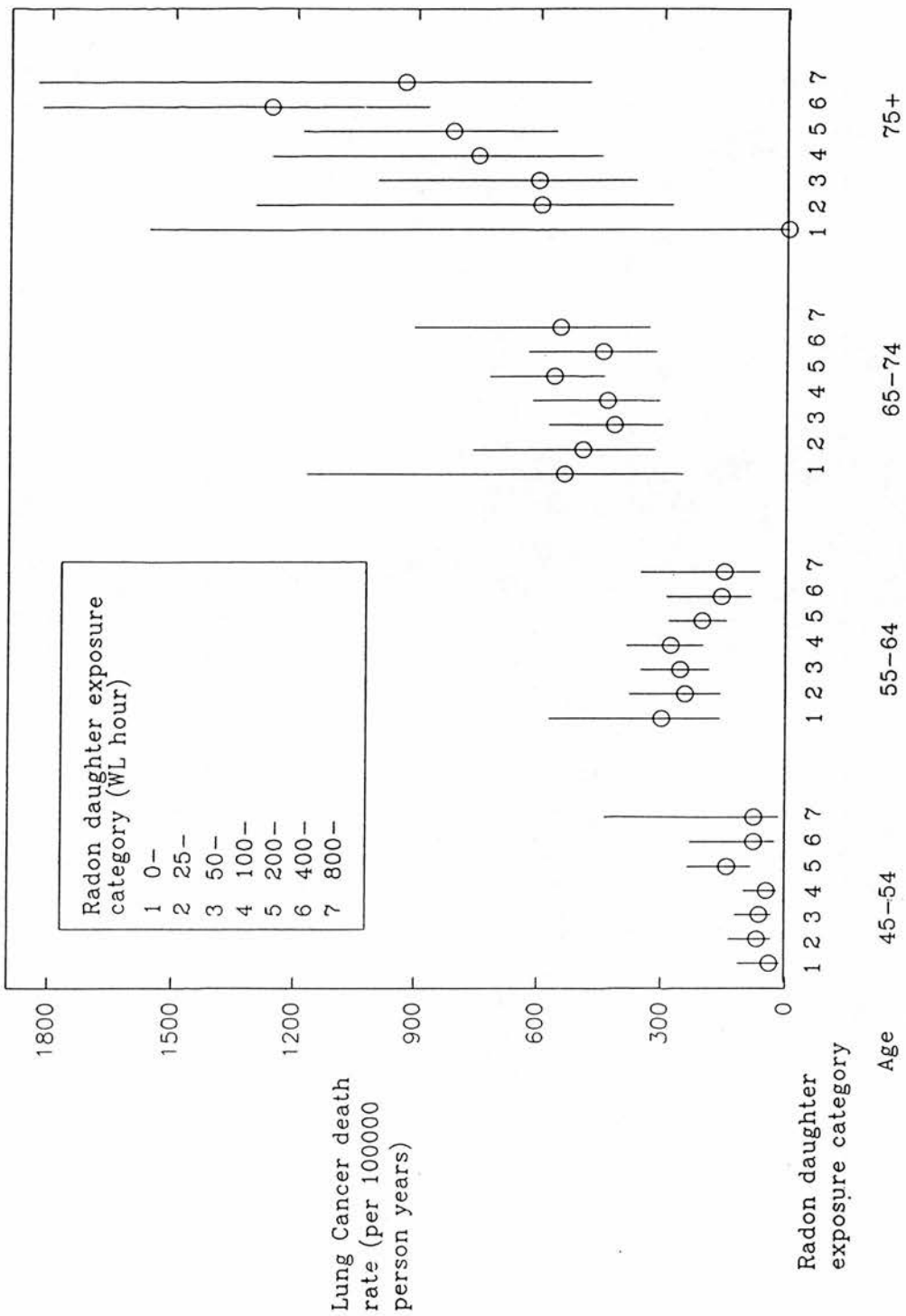

Figure 4.9 Lung cancer death rates per 100000 person–years, by radon daughter exposure category and age. Error bars show 95% confidence limits, based on the Poisson distribution.

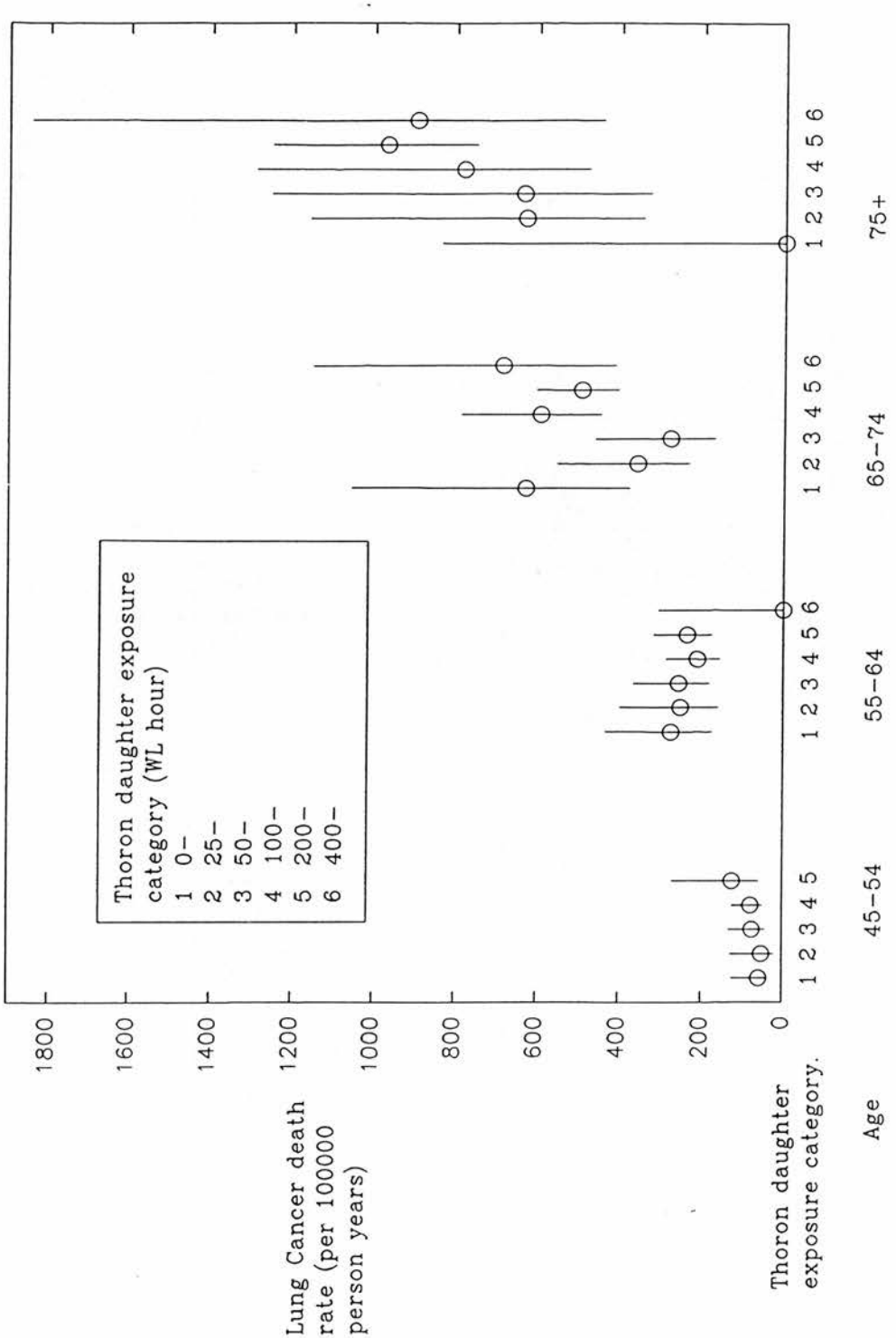

Figure 4.10 Lung cancer death rates per 100000 person-years, by thoron daughter exposure category and age. Error bars show 95% confidence limits, based on the Poisson distribution.

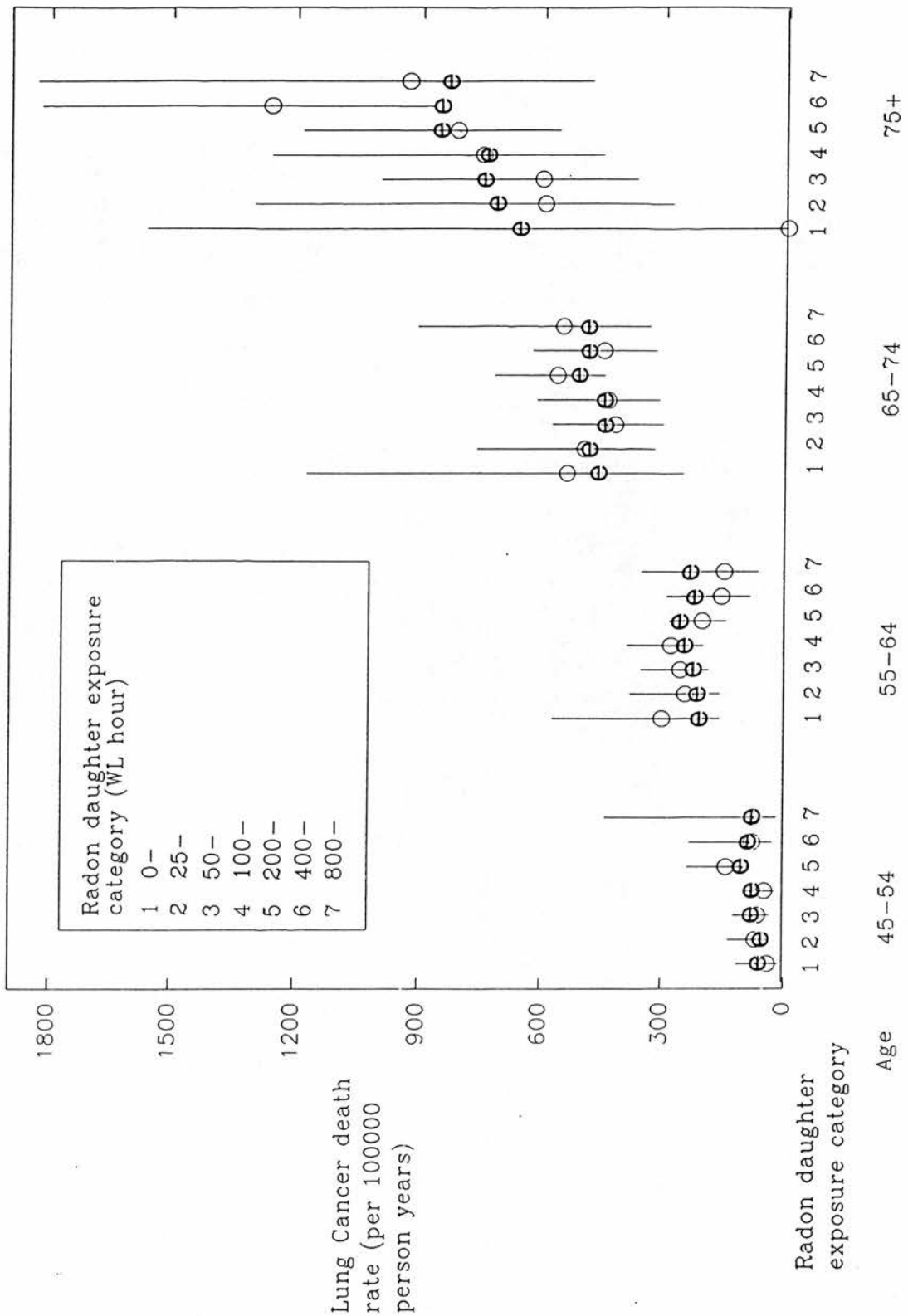

Figure 4.11 Observed lung cancer death rates per 100000 person-years (shown by '0'), with 95% confidence limits; and expected rates (shown by 'e'), predicted by a regression model including radon daughter exposure (see Table 4.9).

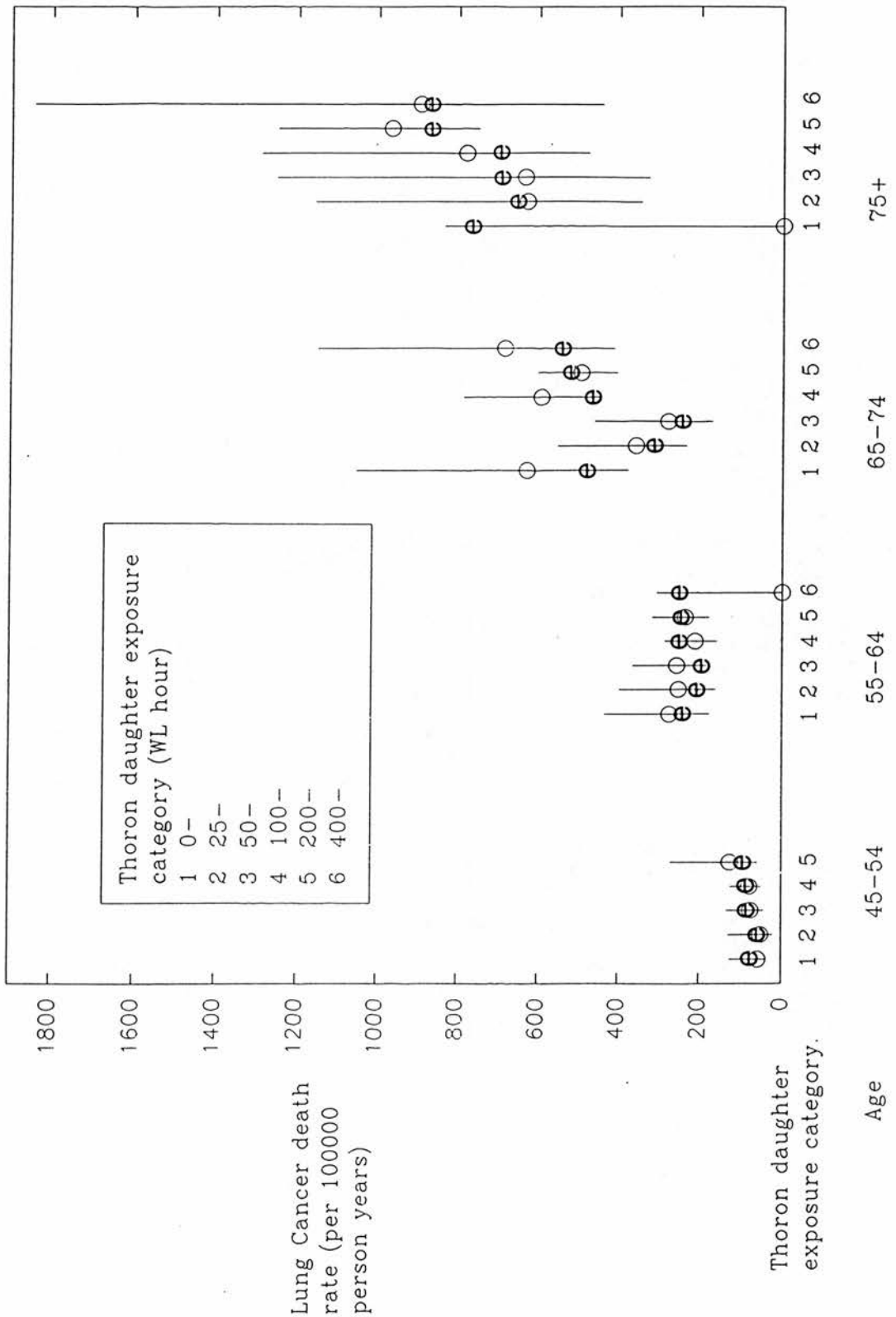

Figure 4.12 Observed lung cancer death rates per 100000 person-years (shown by '0'), with 95% confidence limits; and expected rates (shown by 'e'), predicted by a regression model including thoron daughter exposure (see Table 4.9, with 'thoron' substituting for 'radon').

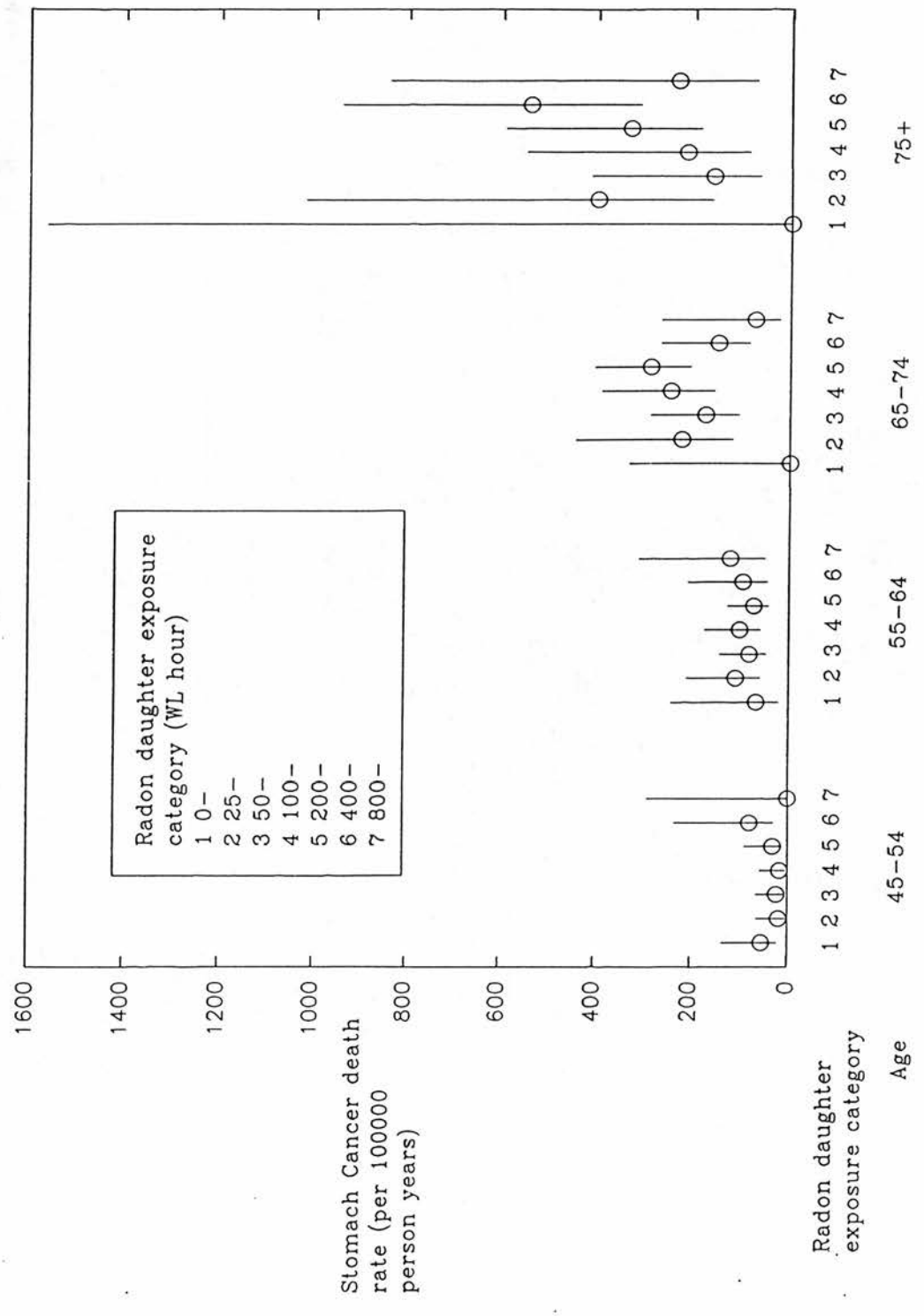

Figure 4.13 Stomach cancer death rates per 100000 person–years, by radon daughter exposure category and age. Error bars show 95% confidence limits, based on the Poisson distribution.

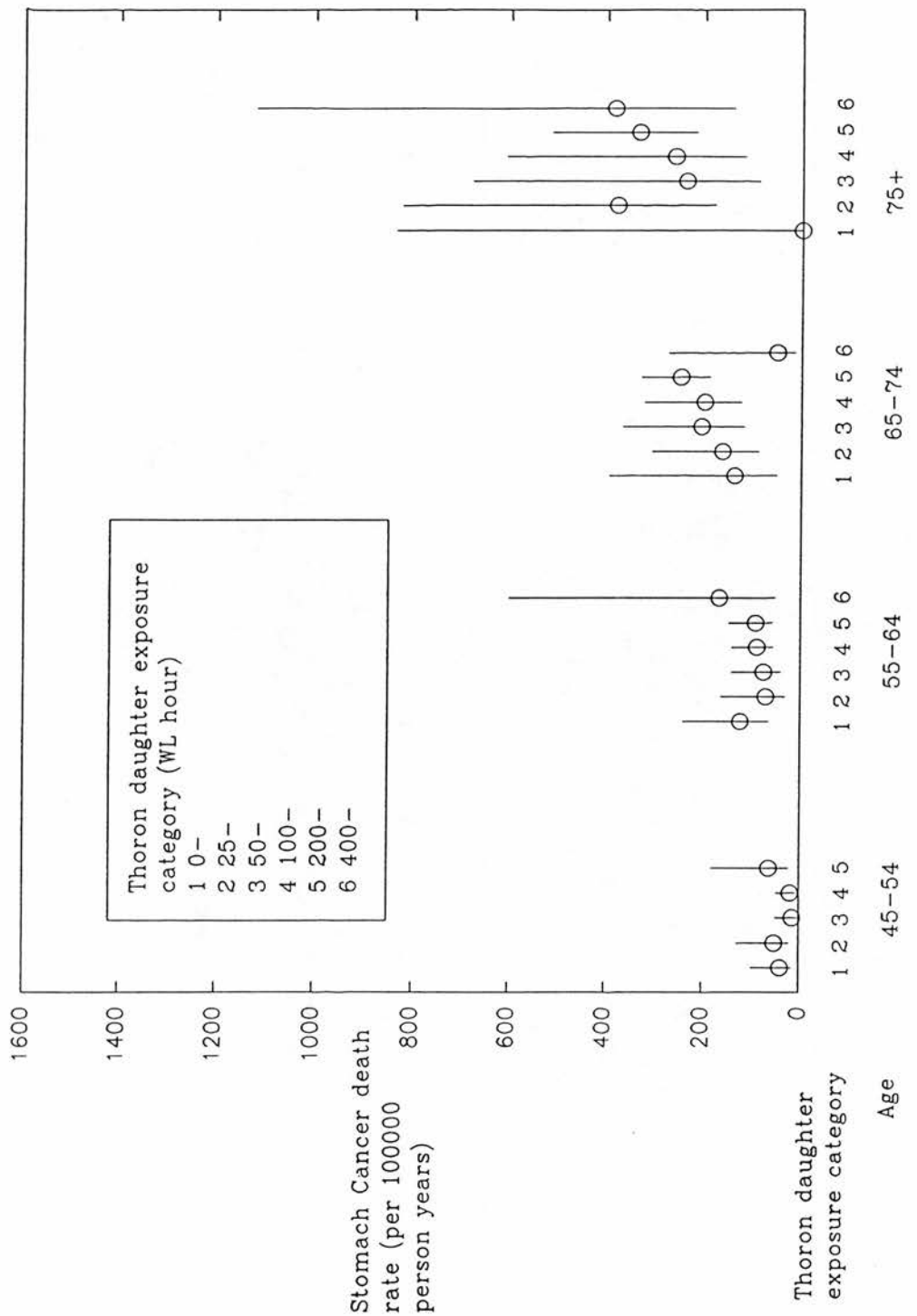

Figure 4.14 Stomach cancer death rates per 100000 person-years by thoron daughter exposure category and age. Error bars show 95% confidence limits, based on the Poisson distribution.

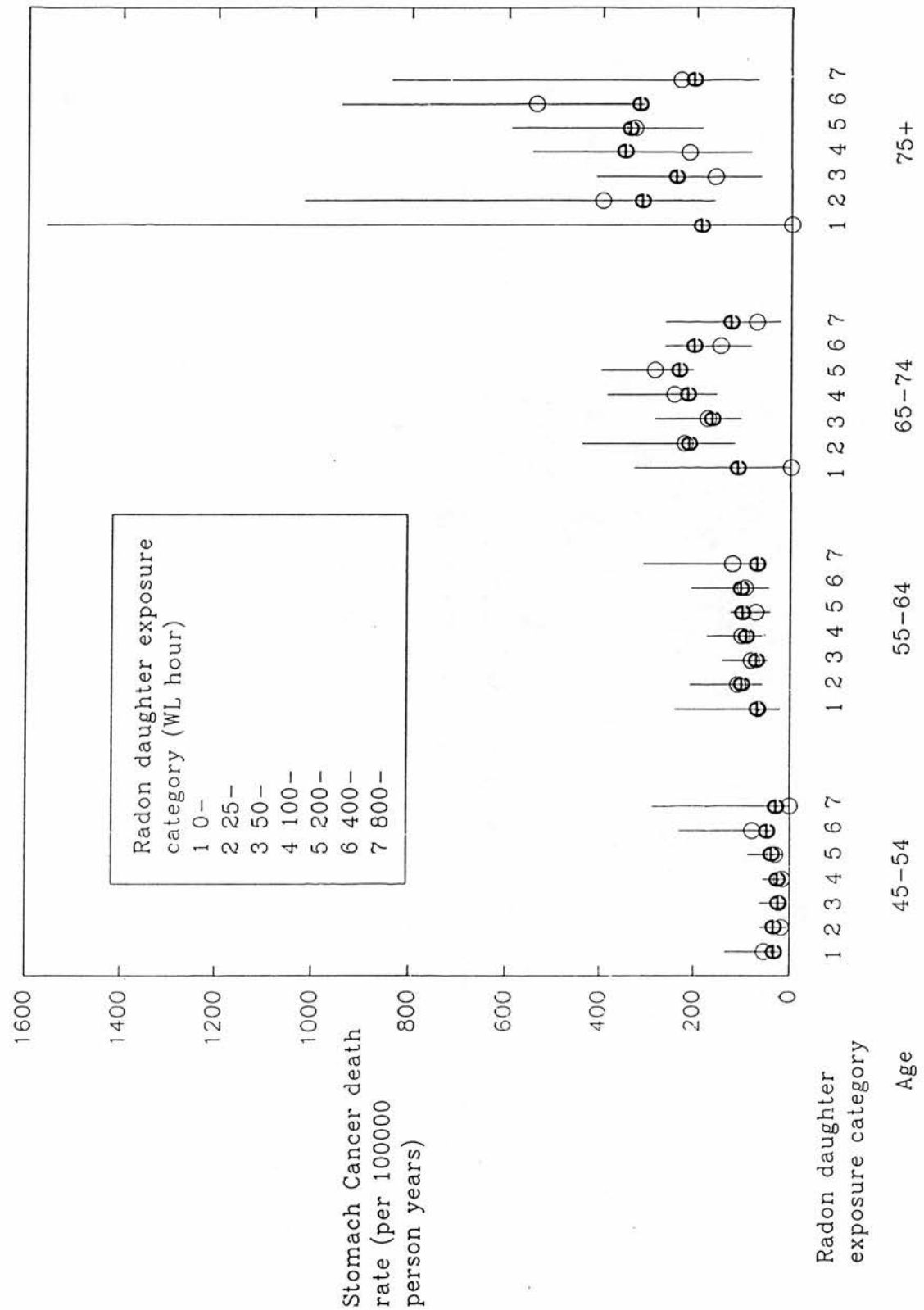

Figure 4.15 Observed stomach cancer death rates per 100000 person–years (shown by '0'), with 95% confidence limits; and expected rates (shown by 'e'), predicted by a regression model including radon daughter exposure (see Table 4.18).

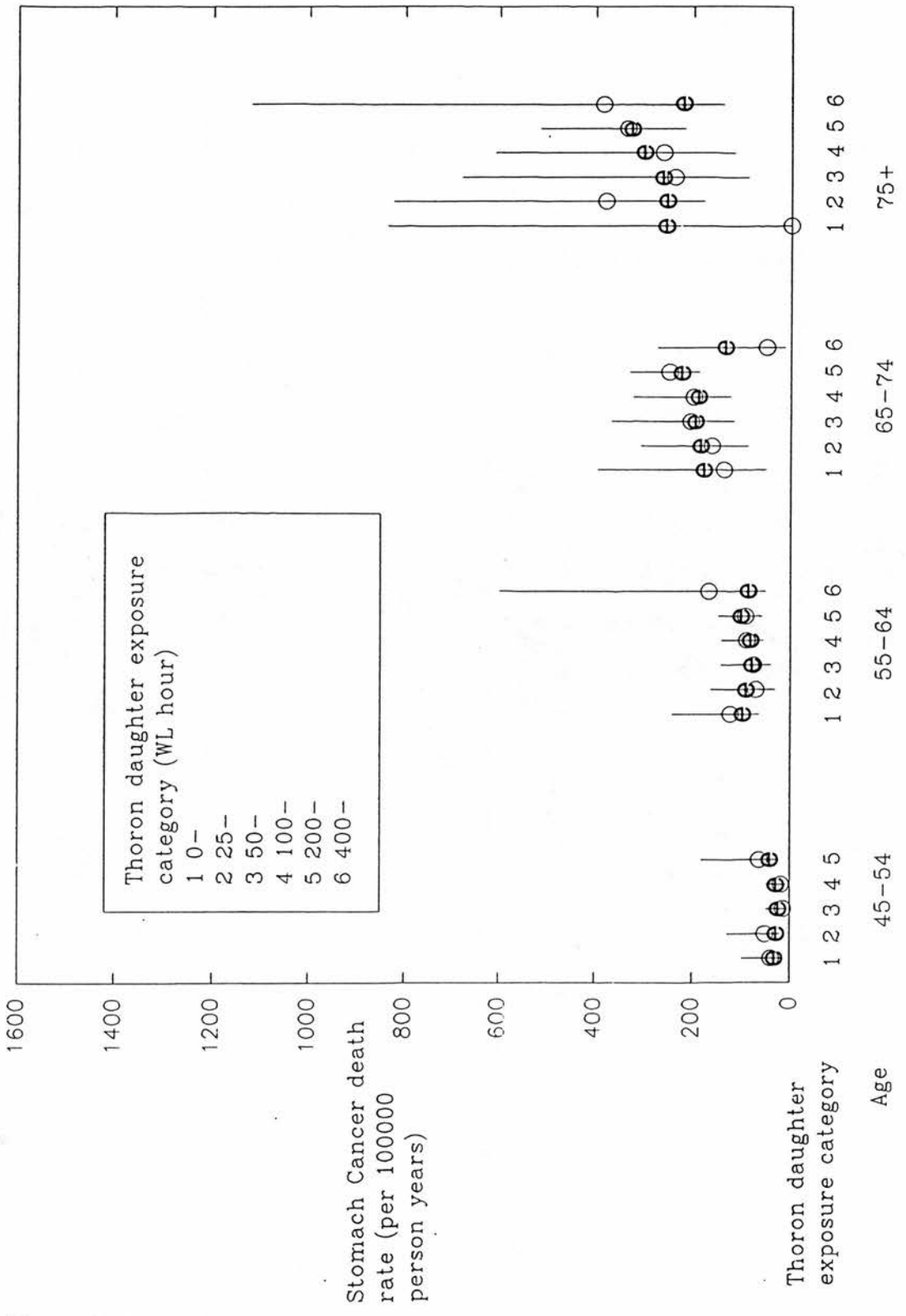

Figure 4.16 Observed stomach cancer death rates per 100000 person-years (shown by '0'), with 95% confidence limits; and expected rates (shown by 'e'), predicted by a regression model including thoron daughter exposure (see Table 4.18, with 'thoron' substituting for 'radon').

Table 4.1 Numbers of men, by colliery and PFR survey at which risk period began. Dates of survey (month/year) are shown below numbers of men.

Colliery	Men	Median age at start	PFR Survey 2	3	4	5	6
C	1394	50	1130 (5/60)	249 (7/65)	4 (10/71)	11 (10/75)	-
F	884	46	690 (2/62)	148 (2/67)	9 (5/72)	37 (4/76)	-
K	1157	46	942 (5/62)	137 (5/68)	6 (10/73)	72 (11/76)	-
P	1155	44	0 (4/58)	1058 (2/64)	27 (11/70)	69 (10/74)	1 (11/78)
Q	1228	38	1191 (6/59)	10 (5/65)	7 (5/71)	20 (6/75)	-
T	1350	45	1171 (3/60)	173 (3/66)	2 (3/70)	3 (6/73)	1* (10/78)
V	1762	39	1706 (6/58)	39 (6/64)	12 (6/70)	1 (6/74)	4 (5/78)
W	654	43	517 (11/61)	114 (11/66)	11 (9/72)	12 (8/76)	-
X	1330	43	996 (5/61)	269 (5/67)	11 (4/73)	54 (3/77)	-
Y	1447	45	1204 (6/59)	230 (5/65)	10 (3/71)	3 (3/75)	-
All	12361	44	9547	2427	99	282	6

* PFR6 was held at collieries P,V only. The man at colliery T whose date of entry was 'PFR6' attended for the first time in Phase 2 at Follow-up Survey, which was held at colliery T five years after PFR5.

Table 4.2 Summary statistics on smoking habit, by PFR survey, for five overlapping sub-cohorts of the study group.

Survey	Date	No. of men giving information on smoking	Smoking group (%)									Mean cigarettes per day
			non-	ex-	pipe	cigarettes per day						
						1-5	6-10	11-20	21-30	31-40	41-	
2	1958-62	10706	14	6	6	5	21	36	11	1	0	10.8
3	1964-68	8629	12	11	6	3	17	38	11	1	0	10.8
4	1970-73	4883	13	15	7	3	11	36	12	2	1	10.7
5	1973-77	4755*	13	21	7	4	10	30	12	3	1	9.9
6†	1978	518*	13	22	5	4	6	28	16	5	1	11.2

* Includes ex-miners seen at Follow-up Survey
† Colliery P, V only

Table 4.3 Summary statistics on smoking habit, by PFR survey, for 2942 men providing smoking information at PFR2, 3, 4, 5.

Survey	Date	Smoking group (%)									Mean cigarettes per day
		non-	ex-	pipe	cigarettes per day						
					1-5	6-10	11-20	21-30	31-40	41-	
2	1958-62	16	5	5	4	20	36	12	2	0	11.2
3	1964-68	14	11	5	4	16	38	10	1	0	10.6
4	1970-73	14	15	6	3	11	36	12	2	1	10.6
5	1973-77	13	20	7	3	9	31	12	3	1	10.2

Table 4.4 Mean cumulative exposures to radon and thoron daughters to end-dates of the listed ISPs, for eight overlapping sub-cohorts of the study group (standard deviations in brackets).

ISP	End-date of ISP	No. of men with time worked in the ISP	Mean cumulative exposure to end-date of ISP (WL hour)	
			Radon daughters	Thoron daughters
0	1954-56	11196	152 (205)	100 (94)
1	1958-62	12339	178 (230)	116 (104)
2	1964-68	9225	209 (248)	136 (106)
3	1970-73	9105	238 (274)	156 (114)
4	1973-77	5605	253 (282)	161 (111)
5	1978-80	3832	268 (303)	167 (112)
6*	1979-80	1762	258 (311)	152 (110)
7†	1980	221	140 (56)	156 (68)

* Collieries C, F, P, Q, V, W, Y only
† Colliery P only

Table 4.5 Mean radon daughter levels (mWL) at 10 PFR collieries, derived from three data sources.

Colliery	Source of data							
	IOM Report TM/82/13			Existing British Coal (BC)			Special BC/NRPB surveys	
	Date	Mean (s.d.)	No.	Date	Mean (s.d.)	No.	Date	Mean (s.d.) No.
C	Dec 1976-Feb 1977	4.0 (3.0)	10	Dec 1985	2.7 (-)	1	Aug 1990	18.5 (7.5) 26
F	Aug 1976-Sept 1976	1.0 (0.6)	9	Jan 1984 Sept 1989-May 1990	4.3 (4.9) 3.2 (2.0)	5 19	-	-
K	Nov 1972-Dec 1972	8.5 (3.9)	8	-	-		-	-
P	Apr 1976-May 1976	3.3 (1.2)	9	-	-		-	-
Q	Apr 1972-Nov 1972 Jun 1979-Jun 1980	17.2 (6.4) 21.4 (10.8)	31 24	Nov 1985	16.1 (-)	1	-	-
T	Jan 1973-Feb 1973	6.5 (2.4)	8	-	-		-	-
V	Oct 1973-Mar 1974	2.0 (1.3)	17	Jan 1984	9.2 (5.6)	5	-	-
W	Apr 1974	1.4 (0.6)	6	Jan 1984	4.7 (7.1)	5	-	-
X	Feb 1976	1.1 (1.1)	9	Dec 1985-May 1986	7.7 (4.3)	8	-	-
Y	Apr 1978-Feb 1979	5.3 (2.6)	15	Jul 1983 Jun 1986	16.2 (-) 12.0 (-)	1 1	May 1990	7.4 (6.2) 24

Table 4.6 Mean thoron daughter levels (mWL) at 10 PFR collieries, derived from two data sources.

	Source of data				
	IOM Report TM/82/13			Special British Coal/ NRPB surveys	
Colliery	Date	Mean (s.d.)	No.	Date	Mean (s.d.)
C	Dec 1976-Feb 1977	4.3 (2.9)	10	Aug 1990	9.1 (8.6) 25
F	Aug 1976-Sept 1976	0.6 (0.1)	9	-	-
K	Nov 1972-Dec 1972	4.4 (2.2)	8	-	-
P	Apr 1976-May 1976	3.7 (0.8)	9	-	-
Q	Apr 1972-Nov 1972	6.6 (1.7)	31	-	-
	Jun 1979-Jun 1980	6.8 (2.3)	24		
T	Jan 1973-Feb 1973	3.5 (0.8)	8	-	-
V	Oct 1973-Mar 1974	1.3 (0.7)	17	-	-
W	Apr 1974	1.6 (0.3)	6	-	-
X	Feb 1976	3.1 (0.9)	9	-	-
Y	Apr 1978-Feb 1979	3.9 (1.1)	15	May 1990	14.2 (9.6) 24

Table 4.7 Average ages at the ends of PFR records of exposure; estimated average cumulative indoor exposure to radon daughters (WL hour) at these ages; average overall cumulative exposure to radon daughters (WL hour) gained during working time.

Colliery	Age	Average cumulative indoor exposure (WL hour)	Mean working-time cumulative exposure (WL hour)
C	57	833	216
F	54	503	54
K	54	790	400
P	54	759	147
Q	51	744	805
T	52	1159	333
V	50	847	88
W	54	878	72
X	53	1073	58
Y	56	1244	272

Table 4.8 Numbers of observed and expected deaths in the study group from all causes and lung cancer, with SMRs and 95% confidence intervals in brackets. (Expected numbers are based on regional death rates).

Age	Cause of death						Person-years at risk
	All causes			Lung cancer			
	obs	exp	SMR (95% C.I.)	obs	exp	SMR (95% C.I.)	
15-24	5	5.1	98 (32, 229)	0	0.0	-	4826
25-34	28	24.5	114 (76, 165)	0	0.4	0 (0, 922)	22547
35-44	120	121.6	99 (82, 118)	6	6.7	90 (33, 195)	48961
45-54	488	534.9	91 (83, 100)	47	55.4	85 (62, 113)	71784
55-64	1504	1595.5	94 (90, 99)	162	203.7	80 (68, 93)	74562
65-74	2342	2298.9	102 (98, 106)	208	245.5	85 (74, 97)	44022
75-	1365	1511.7	90 (86, 95)	98	88.1	111 (90, 136)	11928
All ages	5852	6092.2	96 (94, 98)	521	599.7	87 (80, 95)	278629

Table 4.9 Analysis of deviance of lung cancer death rate, in relation to radon daughter exposure.

Factor	df	Deviance
Age (A)	5	488.55***
+ Smoking habit	5	208.72***
+ Colliery	9	16.51
+ Calendar time (T)	2	7.36*
+ A.T	10	22.90*
+ Radon	6	1.83
Residual	3797	1123.79
Total	3834	1869.65

* $P < 0.05$; *** $P < 0.001$

Table 4.10 Estimated lung cancer death rates* per 100,000 person-years, by:-

(a) Age and calendar time period.
(b) Smoking habit (lagged by five years).
(c) Colliery.
(d) Cumulative exposure to radon daughters, lagged by 10 years (WL hour).

(a) Calendar time x Age			
	1960-69	1970-79	1980-89
-34	1	1	16
35-44	19	19	1
45-54	108	91	53
55-64	251	282	302
65-74	174	717	709
75-	10	983	1321

(b) Smoking habit		
non-		13
ex-		104
pipe		163
cigarettes:	1-10	282
	11-20	363
	21-	524

(c) Colliery		
	C	236
	F	150
	K	215
	P	164
	Q	282
	T	286
	V	173
	W	134
	X	228
	Y	268

(d) Radon daughter exposure (WL hour)		
	0-	282
	25-	329
	50-	331
	100-	321
	200-	285
	400-	276
	800-	244

* In calculating these rates, a 'baseline' of men at colliery Q aged 55-64 during 1970-79, smoking 1-10 cigarettes per day, with a lagged cumulative exposure of 0-25 WL hour radon daughters was used. Their estimated death rate was 282 per 100,000 person-years.

Table 4.11 Mean radon daughter exposure (WL hour) of men who died of lung cancer (cases) and matched survivors (referents), with case–referent differences and, in brackets, differences divided by estimated standard errors; by age, calendar time, colliery, and smoking category.

Sub-group	Frequencies			Means		Difference ('t')
	Strata	Cases	Referents	Case	Referent	
All men	467	493	1897	275	275	-1 (-0.10)
Age						
39-44	5	5	20	95	91	4 (0.20)
45-49	11	11	40	166	188	-23 (-0.31)
50-54	19	20	78	240	249	-9 (-0.20)
55-59	64	66	262	169	173	-4 (-0.24)
60-64	79	84	330	201	200	2 (0.13)
65-69	119	127	500	312	322	-10 (-0.47)
70-74	83	87	334	301	290	11 (0.62)
75-79	56	61	226	370	390	-20 (-0.47)
80-86	31	32	107	382	335	47 (1.50)
Calendar time						
1960-64	4	4	16	180	175	5 (0.10)
1965-69	52	54	207	204	187	17 (1.02)
1970-74	86	88	343	262	249	12 (0.64)
1975-79	112	119	463	282	286	-5 (-0.31)
1980-84	102	111	422	318	334	-16 (-0.55)
1985-89	111	117	446	274	276	-2 (-0.15)
Colliery						
C	69	77	298	216	222	-6 (-0.65)
F	26	26	103	53	55	-2 (-0.68)
K	36	37	140	413	418	-5 (-0.13)
P	38	40	158	146	150	-4 (-0.35)
Q	46	49	190	889	895	-6 (-0.08)
T	62	67	266	324	356	-32 (-1.51)
V	54	56	203	100	98	2 (0.25)
W	15	15	56	67	65	1 (0.24)
X	52	52	199	64	61	3 (0.98)
Y	69	74	284	301	267	35 (2.24)
Smoking						
Non-	3	3	10	337	230	107 (1.28)
Ex-	31	31	122	326	380	-54 (-0.83)
Pipe	30	31	119	278	281	-3 (-0.09)
Cigarettes: 1-5	26	26	89	258	207	51 (1.53)
6-10	80	81	317	401	348	54 (2.88)
11-20	198	215	857	249	265	-16 (-1.14)
21-30	87	94	360	210	221	-11 (-0.73)
31-40	8	8	19	217	257	-40 (-0.34)
41-	4	4	4	153	210	-57 (-1.76)

Table 4.12 Results of conditional logistic regression analyses of lung cancer death rates upon radon daughter exposure.

Model	Likelihood ratio statistic‡ (X^2)	df
Radon daughter exposure (RADON)	0.02	1
RADON, within age groups	3.39	8
RADON, within calendar time periods	1.54	5
RADON, within collieries	8.62	9
RADON, within smoking categories	17.81*	8

‡ For model 'RADON', the statistic tests the overall effect of radon daughter exposure. For the other models, the statistic tests differences in effect of exposure between categories.

* $P < 0.05$

Table 4.13 Relative risks of lung cancer mortality per increase of 1 WLM radon daughter exposure; by age, calendar time, colliery and smoking category.

Sub-group		Relative risk (95% confidence interval)
All men		0.99 (0.90, 1.10)
Age		
39-44		1.58 (0.02, 127.70)
45-49		0.81 (0.38, 1.73)
50-54		0.94 (0.58, 1.53)
55-59		0.93 (0.62, 1.40)
60-64		0.99 (0.74, 1.34)
65-69		0.93 (0.80, 1.08)
70-74		1.10 (0.85, 1.42)
75-79		0.98 (0.81, 1.17)
80-86		1.35 (0.80, 2.29)
Calendar time		
1960-64		1.20 (0.08, 17.47)
1965-69		1.20 (0.76, 1.90)
1970-74		1.09 (0.84, 1.43)
1975-79		0.94 (0.76, 1.18)
1980-84		0.97 (0.83, 1.14)
1985-89		0.97 (0.80, 1.17)
Colliery		
C		0.83 (0.49, 1.41)
F		0.19 (0.00, 48.51)
K		1.01 (0.72, 1.43)
P		0.86 (0.37, 2.01)
Q		1.00 (0.89, 1.13)
T		0.76 (0.56, 1.03)
V		0.83 (0.23, 2.98)
W		1.56 (0.03, 95.26)
X		3.84 (0.28, 53.61)
Y		1.44 (0.97, 2.12)
Smoking		
Non-		3.40 (0.12, 96.75)
Ex-		0.87 (0.69, 1.11)
Pipe		1.06 (0.69, 1.64)
Cigarettes:	1-5	1.81 (0.80, 4.09)
	6-10	1.43 (1.06, 1.93)
	11-20	0.91 (0.78, 1.05)
	21-30	0.86 (0.65, 1.14)
	31-40	0.83 (0.45, 1.52)
	41-	0.01 (0.00, 35.11)

Table 4.14 Results of conditional logistic regression analyses of lung cancer death rates upon thoron daughter exposure.

Model	Likelihood ratio statistic∓ (X^2)	df
Thoron daughter exposure (THORON)	0.06	1
THORON, within age groups	4.39	8
THORON, within calendar time periods	2.75	5
THORON, within collieries	9.90	9
THORON, within smoking categories	13.48	8

∓ For model 'THORON', the statistic tests the overall effect of thoron daughter exposure. For the other models, the statistic tests differences in effect of exposure between categories.

Table 4.15 Results of conditional logistic regression analyses of lung cancer death rates upon a combined dose measure of radon and thoron daughters.

Model	Likelihood ratio statistic† (X^2)	df
Dose	0.01	1
Dose, within age groups	3.49	8
Dose, within calendar time periods	1.77	5
Dose, within collieries	9.26	9
Dose, within smoking categories	17.47*	8

† For model 'dose', the statistic tests the overall effect of dose. For the other models, the statistic tests differences in the effect of dose between categories.

* $P < 0.05$

Table 4.16 Estimated risks of lung cancer mortality by radon daughter exposure, relative to a baseline exposure category of 0–25 WL hour; with chi–square statistics testing the null hypothesis of all relative risks equal to unity. Results are shown for exposures lagged by 5, 10, 15 and 20 years.

Lag (years)	Person-years at risk	Lung cancer deaths	Radon daughter exposure (WL hour)						Chi square (6 df)
			25-	50-	100-	200-	400-	800-	
5	275495	520	1.61	1.37	1.32	1.31	1.20	1.18	3.43
10	231983	506	1.16	1.17	1.14	1.01	0.98	0.86	1.83
15	176626	455	0.77	0.84	0.86	0.71	0.82	0.65	3.41
20	123625	371	0.95	0.80	0.92	0.94	1.07	0.85	2.17

Table 4.17 Estimated risks of lung cancer mortality by thoron daughter exposures, relative to a baseline exposure category of 0–25 WL hour; with chi–square statistics testing the null hypothesis of all relative risks equal to unity. Results are shown for exposure lagged by 5, 10, 15 and 20 years.

Lag (years)	Thoron daughter exposure (WL hour)					Chi-square (5 df)
	25-	50-	100-	200-	400-	
5	1.04	0.96	1.09	0.97	0.89	1.46
10	0.92	0.93	0.91	0.96	1.05	0.50
15	0.91	0.99	0.90	0.94	1.37	2.21
20	0.71	0.76	1.00	0.89	1.04	4.60

Table 4.18 Analysis of deviance of stomach cancer death rates, in relation to radon daughter exposure.

Factor	df	Deviance
Age (A)	5	205.44***
+ Calendar time (T)	2	7.53*
+ Colliery	9	4.72
+ Smoking habit (S)	5	1.50
+ S.T.	10	19.02*
+ Radon	6	9.72
Residual	3797	747.39
Total	3834	995.32

* $P < 0.05$; *** $P < 0.001$

Table 4.19 Estimated stomach cancer death rates* by 100,000 person-years, by:-

(a) Age.
(b) Smoking habit (lagged by five years) and calendar time period.
(c) Colliery.
(d) Cumulative exposure to radon daughters, lagged by 10 years (WL hour).

(a) Age	-34	1
	35-44	2
	45-54	22
	55-64	68
	65-74	161
	75-	264

(b) Calendar time period x smoking habit

	1960-69	1970-79	1980-89
non-	135	58	69
ex-	122	52	52
pipe	1	71	61
cigarettes: 1-10	89	68	60
11-20	98	95	34
21-	40	86	66

(c) Colliery	C	57
	F	105
	K	49
	P	43
	Q	68
	T	49
	V	78
	W	52
	X	96
	Y	44

(d) Radon daughter exposure (WL hour)	0-	68
	25-	89
	50-	60
	100-	107
	200-	137
	400-	135
	800-	63

* In calculating these rates, a 'baseline' of men at colliery Q aged 55-64 during 1970-79, smoking 1-10 cigarettes per day, with a lagged cumulative exposure of 0-25 WL hour radon daughters was used. Their estimated death rate was 68 per 100,000 person-years.

Table 4.20 Mean radon daughter exposure (WL hour) of men who died of stomach cancer (cases) and matched survivors (referents), with case–referent differences and, in brackets, differences divided by estimated standard errors; by age, calendar time, colliery, and smoking category.

Sub-group	Frequencies			Means		Difference ('t')
	Strata	Cases	Referents	Case	Referent	
All men	195	197	1735	265	269	-4 (-0.27)
Age						
44-49	6	6	59	148	135	13 (0.73)
50-54	9	9	88	152	147	6 (0.20)
55-59	21	21	200	241	224	16 (0.32)
60-64	33	33	302	262	233	30 (0.78)
65-69	50	51	471	241	243	-2 (-0.10)
70-74	39	40	334	265	331	-67 (-1.65)
75-79	24	24	224	418	389	29 (1.25)
80-83	13	13	57	252	266	-14 (-0.24)
Calendar time						
1960-64	3	3	23	163	118	46 (5.61)
1965-69	35	35	327	205	232	-27 (-0.72)
1970-74	43	44	389	242	247	-5 (-0.16)
1975-79	46	47	416	315	292	23 (0.83)
1980-84	38	38	326	273	287	-14 (-0.53)
1985-89	30	30	254	291	298	-7 (-0.20)
Colliery						
C	33	33	309	248	242	7 (0.45)
F	17	17	135	48	55	-6 (-1.93)
K	17	18	153	466	448	19 (0.39)
P	14	14	137	195	169	26 (1.93)
Q	17	17	124	774	904	-130 (-0.88)
T	20	21	187	394	403	-9 (-0.34)
V	29	29	247	108	99	9 (1.04)
W	6	6	46	77	73	4 (0.31)
X	21	21	204	61	62	-2 (-0.36)
Y	21	21	193	291	262	29 (1.45)
Smoking						
Non-	25	25	235	348	366	-18 (-0.41)
Ex-	28	28	251	294	252	42 (2.42)
Pipe	16	17	131	225	261	-35 (-0.70)
Cigarettes: 1-5	8	8	53	170	288	-118 (-0.93)
6-10	33	33	284	212	206	6 (0.53)
11-20	62	63	623	269	232	37 (2.10)
21-30	20	20	154	281	365	-84 (-1.09)
31-	3	3	4	156	417	-261 (-0.88)

Table 4.21 Results of conditional logistic regression analysis of stomach cancer death rates upon radon daughter exposure.

Model	Likelihood ratio statistic∓ (X^2)	df
Radon daughter exposure (RADON)	0.02	1
RADON, within age groups	6.75	7
RADON, within calendar time periods	3.62	5
RADON, within collieries	8.88	9
RADON, within smoking categories	12.34	7

∓ For model 'RADON', the statistic tests the overall effect of radon daughter exposure. For the other models, the statistic tests differences in effect of exposure between categories.

Table 4.22 Relative risks of stomach cancer mortality per increase of 1 WLM radon daughter exposure; by age, calendar time, colliery and smoking category.

Sub-group		Relative risk	(95% confidence interval)	
All men		1.01	(0.86,	1.19)
Age				
44-49		1.15	(0.37,	3.58)
50-54		1.29	(0.20,	8.36)
55-59		1.11	(0.67,	1.84)
60-64		1.39	(0.83,	2.35)
65-69		0.99	(0.71,	1.36)
70-74		0.74	(0.52,	1.03)
75-79		1.33	(0.71,	2.49)
80-83		0.89	(0.41,	1.94)
Calendar time				
1960-64		7.30	(0.20,	266.05)
1965-69		0.89	(0.61,	1.31)
1970-74		0.99	(0.72,	1.36)
1975-79		1.28	(0.85,	1.93)
1980-84		0.90	(0.60,	1.35)
1985-89		0.96	(0.65,	1.42)
Colliery				
C		1.20	(0.54,	2.70)
F		0.00	(0.00,	1.33)
K		1.21	(0.72,	2.04)
P		2.77	(0.54,	14.27)
Q		0.93	(0.77,	1.13)
T		0.87	(0.47,	1.60)
V		1.94	(0.36,	10.53)
W		3.13	(0.01,	1171.86)
X		0.48	(0.01,	22.19)
Y		1.55	(0.72,	3.32)
Smoking				
Non-		0.91	(0.62,	1.33)
Ex-		1.48	(0.84,	2.61)
Pipe		0.84	(0.47,	1.49)
Cigarettes:	1-5	0.67	(0.33,	1.36)
	6-10	1.16	(0.54,	2.48)
	11-20	1.68	(0.97,	2.92)
	21-30	0.78	(0.53,	1.16)
	31-	0.57	(0.11,	2.97)

Table 4.23 Results of conditional logistic regression analysis of stomach cancer death rates upon thoron daughter exposure.

Model	Likelihood ratio statistic† (X^2)	df
Thoron daughter exposure (THORON)	0.34	1
THORON, within age groups	5.08	7
THORON, within calendar time periods	3.10	5
THORON, within collieries	8.68	9
THORON, within smoking categories	8.23	7

† For model 'THORON', the statistic tests the overall effect of thoron daughter exposure. For the other models, the statistic tests differences in effect of exposure between categories.

Table 4.24 Mean radon (Rn) and thoron (Tn) daughter exposure (WL hour) of men who died from the listed causes (cases) and matched survivors (referents) with case-referent differences and, in brackets, differences divided by estimated standard errors.

Cause of death	ICD code (9th rev.)	Frequencies				Means		Difference ('t')
		Strata	Cases	Referents		Case	Referent	
Malignant neoplasm of:								
oral cavity	140-149	16	16	424	Rn	276	259	17 (0.31)
					Tn	191	170	21 (0.95)
oesophagus	150	39	39	739	Rn	264	348	-84 (-1.72)
					Tn	163	198	-35 (-1.75)
larynx	161	1	1	38	Rn	235	884	-649 (-)
					Tn	82	311	-229 (-)
bone	170	2	2	40	Rn	137	124	13 (7.25)
					Tn	125	110	15 (3.93)
Malignant melanoma	172	4	4	56	Rn	139	133	7 (0.36)
					Tn	141	134	7 (0.35)
Malignant neoplasm of:								
prostate	185	70	70	1243	Rn	268	257	11 (0.51)
					Tn	191	185	6 (0.49)
kidney	189	14	14	295	Rn	261	219	42 (1.50)
					Tn	178	159	19 (1.12)
Leukaemia (excl. chronic lymphoid)	204-208 (excl. 204.1)	21	21	334	Rn	272	289	-18 (-0.27)
					Tn	185	178	7 (0.24)

Table 4.25 Results of conditional logistic regression analyses of cause-specific death rates upon radon and thoron daughter exposure.

(a) Likelihood ratio statistics (X^2 on 1 df).
(b) Relative risks per WLM, with 95% confidence intervals in brackets.

Cause of death	ICD code (9th rev.)		(a) X^2	(b) Relative risk
Malignant neoplasm of:				
oral cavity	140-149	Rn	0.08	1.07 (0.65, 1.76)
		Tn	0.78	1.62 (0.53, 4.99)
oesophagus	150	Rn	7.51**	0.66 (0.47, 0.91)
		Tn	5.89*	0.47 (0.26, 0.85)
larynx	161	Rn	1.61	0.62 (0.25, 1.57)
		Tn	1.73	0.23 (0.01, 4.08)
bone	170	Rn	0.19	3.92 (0.01, 2390.36)
		Tn	0.22	3.97 (0.01, 1917.70)
Malignant melanoma	172	Rn	0.58	16.22 (0.01, 31780.24)
		Tn	0.53	11.08 (0.01, 11415.46)
Malignant neoplasm of:				
prostate	185	Rn	0.12	1.05 (0.80, 1.38)
		Tn	0.16	1.10 (0.68, 1.78)
kidney	189	Rn	2.25	2.34 (0.65, 8.47)
		Tn	1.05	2.36 (0.42, 13.46)
Leukaemia (excl. chronic lymphoid)	204-208 (excl. 204.1)	Rn	0.18	0.92 (0.65, 1.32)
		Tn	0.12	1.16 (0.49, 2.74)

* $P < 0.05$; ** $P < 0.01$

Table 4.26 Analysis of variance of time worked on surface (1000s of hours).

Source of variation	df	MS
Age	5	8981.2***
Smoking	5	1470.7***
Colliery	9	598.1**
Calendar time period	2	594.0
Residual	7057	221.3
Total	7078	229.0

*** $P < 0.001$ ** $P < 0.01$

Table 4.27 Analysis of variance of time worked underground (1000s of hours).

Source of variation	df	MS
Age	5	337761.4***
Calendar time period	2	17264.5***
Colliery	9	2957.6***
Smoking	5	1628.5**
Residual	7057	339.0
Total	7078	586.4

*** $P < 0.001$ ** $P < 0.01$

Table 4.28 Three percent sample of person-years at risk, by age and time worked on surface lagged by 10 years (1000s of hours).

Time on surface	Age at risk					
	-34	-44	-54	-64	-74	75-
-2	206	643	1126	1257	820	218
-4	51	136	164	128	77	13
-6	46	101	107	86	37	8
-8	39	82	78	53	34	8
-10	40	64	53	55	17	5
-20	56	94	118	102	70	15
-40	0	73	113	139	109	21
-60	0	1	73	91	73	20
-80	0	0	2	42	62	14
>80	0	0	0	1	27	11

Table 4.29 Three percent sample of person-years at risk, by age and time worked underground lagged by 10 years (1000s of hours).

Time under-ground	Age at risk					
	-34	-44	-54	-64	-74	75-
-10	301	309	293	213	157	35
-20	137	407	242	98	48	9
-30	0	361	347	166	45	6
-40	0	117	469	278	76	7
-50	0	0	390	319	112	15
-60	0	0	93	487	173	23
-70	0	0	0	360	233	42
-80	0	0	0	33	360	75
>80	0	0	0	0	122	121

Table 4.30 Summary statistics of times lagged by 10 years worked on the surface and underground (1000s of hours) in a random sample of 7079 person-years, by age at risk.

	Age at risk					
	⩽ 34	⩽ 44	⩽ 54	⩽ 64	⩽ 74	⩾75
No of person-years	438	1194	1834	1954	1326	333
Mean surface time	4.37	4.86	6.03	7.68	11.51	12.07
Mean underground time	7.13	16.92	28.39	42.35	54.21	64.27
Variance surface time	19.69	53.54	136.05	240.38	456.14	542.94
Variance underground time	25.05	98.17	233.73	400.01	661.56	745.29
Covariance	-12.58	-41.15	-108.62	-213.25	-425.45	-540.05
Correlation	-0.566	-0.568	-0.609	-0.688	-0.774	-0.849

Table 4.31 Values of the factors k_j, by age at risk and colliery, for radon and thoron daughter exposure.

Exposure	Colliery	Age at risk					
		-34	35-44	45-54	55-64	65-74	75-
Radon daughter	C	1.20	1.25	1.29	1.36	1.37	1.46
	F	1.40	1.32	1.36	1.47	1.58	1.79
	K	1.09	1.11	1.13	1.16	1.16	1.19
	P	1.07	1.08	1.09	1.11	1.11	1.14
	Q	1.01	1.02	1.02	1.02	1.02	1.03
	T	1.06	1.07	1.08	1.10	1.11	1.13
	V	1.15	1.15	1.17	1.21	1.23	1.29
	W	1.23	1.21	1.24	1.30	1.35	1.44
	X	1.67	1.69	1.81	2.08	2.28	2.75
	Y	1.06	1.07	1.08	1.10	1.11	1.13
Thoron daughter	C	1.16	1.20	1.22	1.28	1.28	1.34
	F	1.66	1.35	1.35	1.41	1.58	1.75
	K	1.11	1.13	1.15	1.18	1.19	1.23
	P	1.03	1.03	1.03	1.03	1.04	1.04
	Q	1.01	1.01	1.01	1.01	1.01	1.01
	T	1.04	1.04	1.04	1.05	1.05	1.06
	V	1.18	1.14	1.15	1.18	1.20	1.25
	W	1.10	1.06	1.07	1.08	1.09	1.11
	X	1.05	1.05	1.06	1.07	1.07	1.09
	Y	1.03	1.03	1.03	1.04	1.04	1.05

5. DISCUSSION

5.1 Lung Cancer

5.1.1 External comparisons

Comparison with regional male population death rates showed lower than expected numbers of deaths from lung cancer, and also from all causes of death, a result which may in part reflect the so-called healthy worker selection effect (Fox and Collier, 1976). It cannot be concluded from this result that the low levels of radioactivity in these mines presented no hazard to health. What can be safely stated is that, even if underground radon and thoron daughters were responsible for some lung cancer deaths, these were not sufficiently numerous to have increased the death rate beyond that of the general population. This does not preclude the possibility that radioactivity has contributed to lung cancer mortality.

5.1.2 Internal comparisons

Exposure-response was examined by two types of mortality analysis, both carried out entirely within the study group. In the event, neither of these - the person-years-at-risk analysis or the case-referent studies - demonstrated a positive association between radioactivity exposure and lung cancer mortality, which held uniformly throughout the study group. (In case-referent studies, an interaction between exposure and smoking was demonstrated, which is discussed in more detail below.)

Although no overall associations with exposure were demonstrated, it is of interest to examine the range of relative risks which were consistent with the data. The following Table shows estimated relative risks, with 95% confidence limits in brackets. The upper limits to confidence intervals may be taken as estimates of the maximum relative risk consistent with the data. (Estimates were obtained from person-years analysis by attaching a mean exposure value to each cell of the table, as explained under methods, and

fitting a single degree of freedom for trend. Results from the two analyses agree reasonably well.)

	Person-years analysis	Case-referent studies
Radon daughters (per WLM)	0.977 (0.896, 1.064)	0.993 (0.901, 1.095)
Thoron daughters (per WLM)	1.051 (0.878, 1.258)	1.024 (0.840, 1.247)
Dose (per 10 mSv)	-	0.996 (0.915 1.085)

5.1.3 Comparison with BEIR IV model

Relative risks predicted by the BEIR IV Committee's Time Since Exposure (TSE) model (National Research Council, Committee on the Biological Effects of Ionizing Radiations, 1988) are consistent with estimates obtained in the present study. The TSE model predicts the risk of lung cancer mortality at a given age in a radon daughter exposed group relative to a non-exposed group, by:

$$1 + 0.03\ (w_1 + \tfrac{1}{2} w_2) \text{ if age } < 55;$$

$$1 + 0.025\ (w_1 + \tfrac{1}{2} w_2) \text{ if } 55 \leqslant \text{age} \leqslant 64;$$

$$1 + 0.01\ (w_1 + \tfrac{1}{2} w_2) \text{ if age} \geqslant 65,$$

where w_1 is the cumulative exposure acquired between 5 and 15 years before the given age, and w_2 is the exposure acquired more than 15 years before. This is a more complex model than any used in the present study, and some simplifying assumptions were made to allow comparison. An age of 60 was chosen for purposes of illustration, and cumulative exposure was assumed to have been acquired at a constant rate from birth. Therefore, if the total cumulative exposure to age 60 is w (in units of WLM), then

$w_1 = {}^1/_6\ w,$

$w_2 = {}^3/_4\ w,$

and the TSE predicts a relative risk of

$$1 + 0.025\ ({}^1/_6\ w + \tfrac{1}{2} \times {}^3/_4\ w),$$

which equals

$$1 + 0.035\ w.$$

Both the person-years and case-referent methods, as implemented in the present study, predict the relative risk at age 60 in the form

$$\exp\ ({}^5/_6\ w\beta)$$

where β denotes the fitted regression coefficient, and the factor ${}^5/_6$ accounts for the 10-year lag.

Figure 5.1 shows both relative risk functions (TSE model and present estimate obtained from person-years analysis) over the range 0-10 WLM, with upper and lower limits for the present estimate based on the 95% confidence interval for the parameter β. (Nearly all of the estimated exposures for the study group were less than 10 WLM - see Figure 4.5, for example. Sixty years indoor exposure to a radon concentration of 40 Bq m^{-3}, assuming 70% occupancy and an equilibrium factor of 0.5, would amount to approximately 11.7 WLM.) It may be noted that the TSE estimate falls within the limits on the present estimate. According to the TSE model, exposure to 10 WLM would increase death rates by 35%; the upper limit to the increase estimated from the present study's results is 68%.

5.1.4 The interaction with smoking

The case-referent studies of radon daughter exposure and of the combined dose measure each showed associations between lung cancer mortality which varied with smoking category. The interaction between thoron daughter exposure and smoking was not statistically significant, but estimated relative risks showed a pattern of variation similar to that shown for the other two variables.

For completeness, these risks are given below:

Smoking group	Relative risk per WLM (95% limits)
Non-	3.26 (0.12, 88.15)
ex-	0.75 (0.41, 1.37)
pipe	1.10 (0.50, 2.43)
cigarettes: 1-5	2.81 (0.75, 10.48)
6-10	1.78 (1.03, 3.05)
11-20	0.87 (0.65, 1.17)
21-30	0.92 (0.55, 1.55)
31-40	0.73 (0.16, 3.26)
41-	0.01 (0.00, 90.55)

Tests for trend in non- and cigarette smokers only (i.e. excluding pipe and ex-smokers) were highly statistically significant for all three measures of radioactivity - the two daughter exposures, and the combined measure of dose. Using single degree-of-freedom terms for exposure and cigarette consumption, the estimated relative risk per WLM radon daughter exposure in non-smokers was 1.50 ($P = 0.008$), and the estimated trend in relative risk was x0.77 per 10 cigarettes per day ($P = 0.004$). Corresponding results for thoron daughters were 1.98 per WLM ($P = 0.013$) and x0.66 per 10 cigarettes per day ($P = 0.011$); and for dose, 1.41 per 10 mSv ($P = 0.007$) and x0.80 per 10 cigarettes per day ($P = 0.004$).

In person-years analysis (all collieries), interactions between exposure and smoking were not statistically significant, but the same pattern was evident:

Smoking group	Relative risk per WLM	
	Radon daughters	Thoron daughters
Non-	1.00	1.46
Ex-	1.03	1.00
Pipe	1.02	1.28
Cigarettes: 1-10	1.04	1.32
11-20	0.92	0.97
21-	0.90	0.87

This pattern was found again in the person-years analysis at colliery Q (Appendix 6), but was not statistically significant.

A similar result was reported by Schoenberg *et al* (1990) in a case control study of lung cancer and indoor radon exposure in 835 New Jersey women. Lung cancer risks increased with increasing radon exposure in smokers of less than 25 cigarettes per day, but apparently declined with increasing exposure in heavier smokers (see Section 1.6). The authors speculated that a thickened mucus layer in heavy smokers might have protected the bronchial epithelium from alpha radiation, thereby weakening the exposure effect. However, such a mechanism would not account for the apparently negative effect of exposure in the heaviest smokers, a feature of the present study also. Two studies of Swedish metal miners - Axelson and Sundell (1978), Radford and St Clair Renard (1984), see Section 1.6 - gave results consistent with a reduced relative risk of radon daughter exposure in heavier smokers; and a case-referent study of Axelson *et al* (1988) found that in rural areas of Central Sweden, risks increased with increasing exposure in non-, passive, and occasional smokers, but fluctuated in smokers, declining to below unity in the highest exposure category. In urban areas, risks declined for both smokers and non-smokers.

In view of the large number of statistical tests carried out during the present analysis, the possibility that the interaction with smoking may be due to chance should be considered. Ten causes of death have been analysed, and 14 tests of interaction between exposure and other factors carried out for four of these causes. The use of a five percent significance level implies that, on average, between one and two of these tests would have given a significant

result, even if exposure had no effect. However, one would be reluctant to attribute to chance an effect or interaction whose statistical significance far exceeded the conventional level. Considered as a decreasing trend, the present interaction falls into this category. The fact that other studies have shown either a similar pattern of interaction, or a pattern consistent with a reduced radon risk in heavier smokers, suggests that an explanation other than 'chance' should be sought for the present result.

It may be that the decreasing trend is a combination of a genuinely weaker exposure–response relationship in heavier smokers, and a biasing mechanism. One possibility is that heavy smokers with chronic sputum production or reduced lung function, would be more likely to transfer from underground to surface work, thereby lowering their exposure. Peto *et al* (1983) have shown that men with mucus hypersecretion have higher lung cancer mortality, allowing for differences in cigarette smoking. By this selection mechanism, cigarette smokers with heavy consumption who died from lung cancer, would tend to have had lower exposures on average than their surviving colleagues with similar smoking habit.

5.2 Other Causes of Death

Of the nine other causes of death analysed in this study, only oesophageal cancer was found to be associated with exposure to radon and thoron daughters. For both exposures, the relative risk declined with age, and, averaged over all ages, was less than unity. Health–related job changes may partly account for this result. Alcohol consumption is known to be associated with oesophageal cancer (IARC, 1988); it may be that men with heavy consumption were transferred to surface work, thereby lowering their radon daughter exposure.

Risks for leukaemia, which has been highlighted in a recent correlation study (Henshaw *et al*, 1990), did not approach statistical significance.

5.3 Exposures to Radon and Thoron Daughters

5.3.1 Implications of results of 1990 surveys

The assumption underlying the method of exposure estimation is that average radioactivity levels within coal seams were approximately constant during the period when study group members were working miners. This is a large assumption to make, since the period in question is a long one. Men attending PFR1 in their fifties could have begun mining as early as 1920; men starting their mining work at the time of PFR2 could still be working at the end of the study period (31/12/1989). Existing data from colliery Q did support the assumption – levels of radon and thoron daughters in 1972 and 1979/80 were reasonably close. However, results obtained in 1990 at collieries C and Y showed higher levels than those of the mid to late 1970s. At colliery C, average radon daughter levels were higher by a factor of approximately 4, and thoron daughters by a factor of 2; at colliery Y, radon daughters were only slightly higher but thoron daughters were greater by a factor of approximately 3. It should be noted that measurements from colliery Y were made in a different seam to those of the 1970s, which confounds the comparison of time periods.

The new data (which became available only after statistical analysis of mortality had been carried out) raised a question mark over the validity of the basic assumption underlying exposure calculations. The substantial increase in radon daughters at colliery C was of particular concern, since the new measurements were made in the same seam as previous measurements. Two possible reasons for the increase were related to changes in mining method which had taken place at colliery C since the 1970s (Smith, British Coal Scientific Services, personal communication, 1991). First, the use of a greater extraction thickness in recent years led to a greater proportion of stone and shale, compared to coal, accumulating in waste areas, and this may have increased radon emanation rates, since the rock had a greater concentration of uranium than the coal. Second, at the time of the 1990 survey, access roadways to two production faces were in use, which had been driven through waste material created by the advancing face (so-called 'gob scours'). The walls of the roadways therefore presented a larger surface

area to the coalmine atmosphere than would have been offered by roadways driven through rock. Gob scours were not used at colliery C during the 1960s and '70s.

If the rise in radioactivity level at colliery C can be attributed to changes in mining method which have occurred during the 1980s (although there is no strong evidence that it can) then the assumption of constant levels during the 1970s and before is not explicitly contradicted by the new data. Furthermore, since all but one of the causes of death considered in this study were investigated in relation to exposure lagged by 10 years, and since most of the men studied left the industry before 1980, radioactivity levels during the 1980s were not a major concern. Nevertheless, the main impact of the 1990 surveys upon the present study has been to cast doubt upon the validity of the assumption of long-term constancy of radioactivity levels within seams, and hence, upon the reliability of estimated exposures.

5.3.2 Effects of errors in exposure estimates; some alternative estimation strategies

It is however worthwhile considering the quality of exposure estimates under a model of constant radioactivity levels within seams, even though this assumption must now be regarded with caution. The following discussion focusses on the impact upon relative risk estimates of limitations in exposure assessment; some alternative estimation strategies are also considered.

A useful framework is provided by the identification of four main sources of error given in Section 3.5.4, considering first the sampling error in the estimates of seam mean radioactivity levels. Although few samples were obtained in each seam (five, on average, excluding the High Main Seam at colliery Q where 50 measurements were made), the results of Section 4.6 suggest that the attenuating effect of the random measurement error will have been moderate. Secondly, the analysis of Section 3.5.4 suggests that spatial and temporal variation within seams will not have contributed to this attenuation. In the notation of that Section, the relative risk of mortality per unit estimated exposure x (β') is related to the relative risk of mortality

per unit true exposure z (β) according to

$$\beta = \frac{\text{Var}(x)}{\text{Cov}(x,z)}\,\beta'$$

If the only source of error in exposure estimates were spatial and temporal variation within seam, the term Var(x)/Cov(x,z) would be unity, since the standard errors of estimated seam means (κ_i) would vanish. In that case, the induced model relating death rate y (within stratum) to estimated exposure x (see Section 3.5.3) simplifies as follows,

$$\begin{aligned} E(y|x) &= \exp\{\alpha + \beta E(z|x) + \tfrac{1}{2}\beta^2 \text{Var}(z|x)\} \\ &= \exp\{\alpha' + \beta E(z|x)\} \\ &= \exp\{\alpha' + \beta x\}. \end{aligned} \qquad (1)$$

However, the residual variation in y (given x) for the induced model is greater. This follows from the identity

$$\begin{aligned} \text{Var}(y|x) &= E(\text{Var}(y|x,z)) + \text{Var}(E(y|x,z)) \\ &= E(\text{Var}(y|z)) + \text{Var}\,(E(y|z)), \end{aligned}$$

assuming, as before, that x is uninformative for y given z. In the case where Var(y|z) = cE(y|z), for some constant of proportionality c (i.e. y is proportional to a Poisson variate), the first term on the right hand side of the identity simplifies thus:

$$\begin{aligned} E(\text{Var}(y|z)) &= E(cE(y|z)) \\ &= E(c\,\exp(\alpha + \beta z)|x) \\ &= c\,\exp\,(\alpha + \beta E(z|x) + \tfrac{1}{2}\beta^2 \text{Var}(z|x)) \\ &= c\,\exp(\alpha' + \beta x) \\ &= cE(y|x) \quad \text{from (1) above.} \end{aligned}$$

Therefore, Var (y|x) = cE(y|x) + Var(E(y|z)) > cE(y|x).

Hence, the effect of the failure of exposure estimates to reflect within-seam variation will have been a loss of power, rather than a bias in relative risk estimation.

More power might have been achieved by a more sophisticated assessment of exposure. One approach which was considered, but eventually not used, was based on the idea of using regression functions relating mean radioactivity levels to certain concomitant variables. To be useful, such concomitants had to show a strong relationship with radon and thoron daughter levels, and had to be available, or estimable, for at least the most heavily worked coalfaces current during PFR. Regression equations would have been calculated from available radioactivity data and values of the chosen concomitants pertaining to the locations where the measurements were made. These equations could then have served as 'predictors' of radioactivity levels at other locations and other times for which no measurements were available, using known values of the concomitant variables pertaining to these new locations and times. The method was used successfully by Jacobsen *et al* (1988) in a study of the incidence of respiratory infection in coalminers, in relation to nitrous fume exposure.

Two concomitant variables were considered:

a) ventilation distance - the distance travelled by the ventilating airstream from the intake shaft to the location of interest;

b) ventilation quantity - the volume of air (m^3) passing the location in unit time.

Ventilation distance appeared to have a fairly strong relationship with both radon and thoron daughters (Figs 5.2 and 5.3 respectively); regression analyses confirmed the existence of increasing trends ($P < 0.001$ for Rn, $P < 0.01$ for Tn), after allowing for differences between seams (Tables 5.1 and 5.2). Associations between ventilation quantity and radioactivity levels appeared to show decreasing trends, which were not particularly convincing (Figs 5.4 and 5.5). The effect on radon daughters was not statistically

significant, and on thoron daughters, just reached significance ($P < 0.05$), after allowing for differences between seams (Tables 5.3 and 5.4).

Despite the strength of its relationship with radioactivity levels, ventilation distance was judged unsuitable for use as a concomitant variable given the scope of the present study. This was because it was not available from routine PFR data. In principle, estimates could have been obtained from historical colliery plans, but this exercise would have increased the effort required for exposure estimation, at the expense of resources allocated to mortality analysis. Some consideration was given to using a surrogate variable for ventilation distance, namely, time taken to travel from pit bottom to the coalface, a quantity which was available from routine PFR documentation. Two important objections were, first, that travelling time was an unreliable guide to distance travelled, since it contained unknown components of walking time and time on locomotives, and secondly that routes taken by miners travelling to the coalface did not necessarily reflect the distance travelled by the ventilating airstream.

Ventilation quantity enjoyed an advantage over ventilation distance, in being available from PFR documentation, as a coalface average figure. However, relationships with radon and thoron daughter levels were weak, and mainly for this reason, it was decided not to use the variable in a prediction equation.

In passing, it is worth remarking that it is the detailed nature of the time-worked data in the Attendance Records System which makes the use of ventilation distance a possibility. All coalface Occupational Groups in each colliery were specific to individual faces; when a face closed and the men working on it transferred to another face (or other faces), their time was thereafter recorded against the Occupational Group Serial Number of the new face. Of course, ventilation distance to the face would change as the face advanced or retreated from the roadway. Nevertheless, use of an average figure might have given more accurate estimates of radioactivity than the seam mean.

The third source of error in exposures listed in Section 3.5.4 was errors of measurement in times worked, due to inaccuracies in the Attendance Records

System, or errors of recall. The first of these are likely to be small, since times worked in Occupational Groups were ultimately derived from payroll systems, and can be considered reasonably reliable. Occupational History times were obtained by questionnaire and will contain errors of recall. No information is available on the magnitude of these errors. However, an indication of their impact on relative risk estimates was sought by applying the method of Section 3.5.4, assuming a value for the size of the error. For simplicity, the uncertainty associated with estimates of seam mean radioactivity was ignored. A similar analysis to that of Section 3.5.4 gives 'de-attenuation factors' specific to stratum j:

$$k_j = 1 + \frac{\sigma_0^2\mu_0^2 + \sigma_1^2\mu_1^2}{\nu_0^2\mu_0^2 + 2\nu_{01}\mu_0\mu_1 + \nu_1^2\mu_1^2} .$$

In this equation, symbols μ_i, ν_i, ν_{01} have their previous meanings, and σ_i^2 (i = 0,1) denote variances of errors affecting surface and underground time. (These errors were assumed uncorrelated with each other, and with true, but unknown times.) If σ_i/τ_i (where τ_i denote mean times worked in the underlying population) take the same value for surface and underground time and also for different strata, CV_{error} say, then

$$k_j = 1 + CV_{error}^2 \frac{\tau_0^2\mu_0^2 + \tau_1^2\mu_1^2}{\nu_0^2\mu_0^2 + 2\nu_{01}\mu_0\mu_1 + \nu_1^2\mu_1^2} .$$

Values of k_j were calculated according to the method of Section 3.5.4, with estimates of μ_i, τ_i, ν_i and ν_{01} obtained from Tables 3.7 and 3.8. (Note that $\hat{\nu}_i^2$ will be inflated by the random error whose affect is being assessed.) Assuming a value of 10% for CV_{error}, weighted average values of k_j were 1.05 for both radon and thoron daughters. Although reassuringly small, the k_j increase rapidly with increasing CV_{error}: 1.19 for 20%, 1.40 for 30%.

The fourth source of error is the assignment of colliery mean radioactivity levels to three risk categories: (i) Occupational History time worked underground at both PFR and non-PFR collieries; (ii) Attendance Records

time in seams where no measurements had been made; (iii) Attendance Records time in Occupational Groups working in 'All Seams'.

Considering (i) first, in general estimated exposures of men who had spent a larger proportion of their working time in seams where measurements were made were clearly more reliable. To give an indication of overall reliability, the percentage of each man's total working time in eight mutually exclusive categories was calculated. The results (Table 5.5) showed that only 16% of time, on average, was spent in 'measured seams'; percentages for the three categories mentioned above were 42%, 7% and 14% respectively. Most of the Occupational History time (the 42%) referred to ISP0, a period not systematically documented in PFR reports. A more elaborate assessment of exposure would have required a historical study of each colliery to ascertain which seams were working, and when, during the decades prior to PFR1. However, the usefulness of such information would have been limited by lack of detail in the time-worked data. For example, if two seams were worked at a colliery, Occupational Histories would have given no guide to the proportions of time worked in each. At the outset of the project, it was unclear what benefits, if any, would result from historical investigations given the limitations of the time-worked data, and therefore the decision was made not to allocate project resources to such explorations. Assignment of the colliery mean to Occupational History time was the natural choice.

Limitations of project resources was also a factor in deciding what radioactivity levels to assign to categories (ii) and (iii) above. Underground plans were at hand for some (a minority) of the collieries, which would have given an indication of the proximity of different seams. However, such information would probably have been of limited usefulness, since it is possible that the composition of sedimentary rock strata adjacent to neighbouring seams would vary, especially in the presence of faulting. In any case, plans were not readily available for all collieries, and it was decided that the effort required to obtain as near a complete set as possible of such plans, and also to interpret them, would be better directed elsewhere. This decision was taken before the information in Table 5.5 was available. The fact that only 7% of total time worked, on average, was spent in this category was reassuring, and suggests that 'unmeasured seams' would require to have differed

considerably from those with measurements, to have affected cumulative exposures other than slightly.

Colliery means were also assigned to times worked in Occupational Groups which covered All Seams. This was equivalent to assigning means of seam means, weighted by sample sizes (and hence to a certain extent, by precision). Since differences between seams in radioactivity level were not large, except at colliery Q (which is discussed in more detail below), it was judged likely that the precise choice of weights would not be crucial. However, the method can be criticized on two grounds. First, the particular seams coming under the umbrella of All Seams depend on ISP, and use of single radon and thoron values made no allowance for this. For example, All Seams at colliery Q included either one or two 'measured seams', depending on the period being considered (Figure 5.6). Secondly, use of sample sizes as weights may not be appropriate in a situation where seam means are known to differ, and where individual exposures depend on times spent in various contributing seams. An alternative approach would have been to weight seam means by average times worked in seams, and to allow weights to vary with ISP. This would have ensured that the population mean of that portion of estimated exposure due to work in All Seams was equal to the population mean of the corresponding portion of the true exposure. (However, such 'unbiasedness' would not necessarily protect against bias in the estimation of relative risk, since parameters other than the means of the joint distribution of estimated and true exposure can affect bias in relative risk estimates, as the analysis of Section 3.5.4 shows.) Although in retrospect, time-weighting would probably have been preferable, the average proportion of men's working time spent in All Seams was not large (14%), and use of the more sophisticated approach would probably not have changed exposure estimates substantially. This judgement is further supported by the fact that each 'measured seam' was being worked throughout PFR except at collieries F and Q, see Figure 5.6. (Note that at colliery W, Big Vein(C) and Big Vein (P) refer to the same seam, originally worked from two different collieries.) Thus, in each ISP, each 'measured seam' would have contributed to a weighted mean, except at the two collieries mentioned. At colliery F, levels were so low that the choice of weights was not important. Colliery Q was unique in being the only colliery where a substantial seam

difference was observed: the average radon daughter level in the Waterloo Seam was 6.93 mWL (3 samples), compared to 20.30 mWL in the High Main Seam. (The difference in thoron daughters was much less.) Time-weighting for 1972-76 approximately, might have produced a difference in estimated exposure, but probably not a substantial one in view of the shortness of the period. (Incidentally, the estimates of radioactivity level in the Waterloo Seam, being based on only three samples, would be subject to considerably more uncertainty than those of the High Main Seam, a fact which an optimal weighting system would have to take into account.) During the remainder of the PFR, the only working seam with measurements was the High Main; prior to roughly 1966, it was the only working seam. In the absence of information on the other seams (Main Bright, Low Bright, Second Waterloo, High Hazel), which were all of short duration, use of a mean weighted towards the High Main value for All Seams time was not unreasonable.

The effect on relative risk estimates of the assignment of colliery means to the three categories of underground time discussed above, would be difficult to quantify. If underground levels of radioactivity during ISP0 are reasonably well approximated by colliery means obtained from the 1970s surveys, then the effect may be a loss of statistical power rather than the introduction of bias. This is by analogy with the case already discussed, of the impact upon risk estimates of the use of a single value to describe levels within seams.

To summarize, errors in exposures caused by sampling errors in seam means and recall errors in times worked, will have biased towards unity estimates of relative risk per WLM exposure to radon and thoron daughters. The correction factor for the radon daughter risk is estimated to be 1.25 (1.19 x 1.05 for sampling errors and recall errors respectively), and for the thoron daughter risk 1.16 (1.11 x 1.05). It is suggested that errors in exposure due to the failure of seam and colliery means adequately to reflect spatial and temporal variation in radioactivity, will have caused a loss of statistical power, but not introduced any bias.

These results allow the following adjustments to be made to the upper limits of confidence intervals. Applying the factors to the risk estimates and 95%

confidence limits obtained from person-years analysis and tabulated in Section 5.1, gives the relative risks shown below (the unadjusted risks are given for comparison):

Exposure	Relative risk per WLM	
	adjusted for exposure error	Unadjusted
Radon daughters	0.971 (0.872, 1.081)	0.977 (0.896, 1.064)
Thoron daughters	1.059 (0.860, 1.305)	1.051 (0.878, 1.258)

These adjustments should be regarded as indicating only approximately the size of the bias in relative risks caused by error in exposure estimates. In particular, a model of bivariate normality for the distribution of the observed and true exposures within strata, is unlikely to be a close approximation to the underlying 'true' distribution, in view of the skewness shown in Figures 4.5 and 4.6. Pierce *et al* (1992), considering the 'errors in variables' problem in the context of the A-bomb survivor data, argue that the distributional assumptions concerning true and estimated covariates are critical.

5.3.3 Indoor exposure to radon daughters

If indoor exposure to radon and thoron daughters is associated with increased lung cancer risk, then the potential exists for confounding an association with working-time exposure. Possible consequences upon unbiasedness and precision of relative risk estimates caused by the omission of indoor exposure are considered in this Section. (All references to radon are understood to include thoron.)

Within sub-populations at individual collieries there is no reason to suppose any correlation between domestic concentrations, and underground concentrations of radon to which men were exposed. Factors influencing the former, other than source strength, include weather (temperature and winds),

ventilation conditions, and type of dwelling (radon entry to homes with a ground floor is from underlying soil, but to homes on upper floors of buildings of several storeys, mainly from building materials (Nero, 1988)). Factors influencing underground levels include ventilation distance and probably mining method. Daughter concentrations in the two environments are even less likely to be correlated since they are also affected by the concentration of airborne dust particles: in general, the lower the dust concentration, the lower the equilibrium factor (Nero, 1988).

However, it is possible that a negative correlation between the two cumulative exposures might be induced by an inverse relationship between time at work and time at home. Without knowledge of the occupancy habits of the miners concerned the strength of this relationship cannot be assessed. Two factors would operate to dilute any induced correlation: the fact that, for surface workers, working-time involves no underground exposure, and secondly, the variability of indoor daughter concentrations. The effect of the latter may be shown by a simple model, in which underground concentrations are assumed constant, and indoor concentrations are assumed to vary only between dwellings. Taking exposure as the product of time by concentration, a straightforward calculation shows that the correlation between the exposures is given by

$$\rho_e = \rho_t \frac{cv_t}{\sqrt{\left[cv_c^2 \left[1 + cv_t^2 \right] + cv_t^2 \right]}}$$

where

cv_t = coefficient of variation of indoor time,

cv_c = coefficient of variation of indoor concentration,

ρ_t = correlation between indoor and working time.

If the two components, indoor and working-time exposure, are regarded as separate variables in regression analyses (either of death rates, or in conditional logistic analysis), what has been estimated in the present study is the effect upon death rates (y, say) of working-time exposure (x), unadjusted for the effect of indoor exposure (z). By analogy with ordinary linear regression, one might expect that addition of the indoor component would

approximately reduce the unadjusted coefficient of the working-time exposure by the product

$$\beta_{y/z,\ adj\ x} \cdot \beta_{z/x}$$

where, for example, $\beta_{y/z,\ adj\ x}$ denotes the regression coefficient of z, adjusted for x. If the two components of exposure were negatively correlated, the negative sign of $\beta_{z/x}$ would mean that the 'reduction' would be a numerical increase; if the correlation were sufficiently small, the unadjusted coefficient would change only slightly.

Supposing a negative correlation (ρ_e) to exist, the magnitude of the increase in the unadjusted coefficient would depend not only on the correlation but also on the relative variabilities of x and z, since from ordinary linear regression,

$$\beta_{z/x} = \rho_e \frac{\sigma_z}{\sigma_x}$$

where the σs denote standard deviations. Purely for illustrative purposes, if the ratio of mean indoor exposure to mean working-time exposure (Table 4.7) is taken as a guide to the ratio of their standard deviations, it would appear that for some collieries the quantity σ_z/σ_x could be substantially greater than unity (e.g. 18.5 at Colliery X, 12.2 at Colliery W). The least potential for confounding is likely to be at Colliery Q, where the two components of exposure may have similar standard deviations.

Whether or not the omission of indoor exposure has caused an under-estimation of relative risk, a loss of statistical power will certainly have resulted. This is easily seen in the case where the two exposures are uncorrelated, and their regression coefficients are equal. If indoor exposures were available, the variance of the estimate of the common coefficient would depend inversely on the variance of the total exposure, $\sigma_x^2 + \sigma_z^2$. For some collieries, this quantity may considerably exceed the variance of the working-time component alone, as discussed above. An analysis at Colliery X for example, with indoor exposures available, would reduce the standard

error by about 1/18.5, under assumptions made earlier ($\sigma_X^2/(18.5^2\sigma_X^2 + \sigma_X^2) \doteq 1/18.5^2$). The reduction at Colliery Q would be about 1/1.4. The unweighted mean of these factors over all collieries is approximately 1/7.

To summarize, the omission of the indoor component of exposure may have caused a downward bias in the estimate of relative risk per unit of working-time exposure. Without knowledge of the joint distribution of the two components, an estimate of the potential bias cannot be made. Furthermore, the omission will certainly have caused a loss of statistical power. Rough calculations (made under unverified assumptions) suggest that the use of domestic exposure, had it been available, would have yielded a coefficient of total exposure with a standard error about 1/7 that of the present coefficient of working-time exposure (assuming the two exposures had equal coefficients).

5.4 Completeness of Follow-up; Exclusions from Analysis on Grounds of Missing or Unreliable Data

Three-point-three percent of the study population were excluded from statistical analysis because of unknown vital status. Some of these men had emigrated, and were for practical purposes 'lost to follow-up'; that is, their dates and causes of death will never be known, unless they return to the UK in the future. This group made up 0.7% of the study population. The remaining percentage (2.6%) is not so high as to allow the possibility of a serious bias in the results; efforts to reduce it further are presently being made, through the records of the British Coal Corporation's pension scheme and concessionary fuel department.

After exclusion of the 3.3%, 18769 men remained. Further exclusions on the grounds of missing, or inconsistent data, reduced this number by 34%, giving a group of 12361 men for analysis. The large reduction from the total number of men attending PFR1 or 2, to the number included in analyses, was caused largely by two factors: lack of smoking information at PFR1 (and at PFR2 for one colliery), and absence of time-worked information for Singletons. Unfortunately, these features of PFR data cannot now be

altered – for example, there is no way of retrieving time records for Singletons. The possibility was considered of increasing the study group size in certain analyses, by including men with no smoking information. Thus, for example, since smoking does not appear to be a risk factor for stomach cancer, it might be argued that no adjustment for its effect would be required in estimating relative risks due to radon or thoron daughter exposure. However, inhalation being the principal source of entry of radon and thoron daughters to the body, smoking-related changes to lung structure might affect dosage, not only to the lung, but to other sites also.

Exclusions on the grounds of missing time-worked information will have been greater among older men. This is because men close to retirement age at PFR1 will not have remained in the industry long enough to attend PFR2, and consequently will have become Singletons. Although a disproportionately high number of deaths will therefore have been excluded, exposure-response relationships should not have been biased, since losses will not have been related to exposure.

5.5 Statistical Methods

5.5.1 Treatment of exposure variables, and smoking

In person-years analyses (internal and external comparisons) and case-referent studies, cumulative exposure measures were continuously updated throughout the study period. Linear interpolation was used to estimate exposure to dates between surveys; since ISPs lasted only five years on average, this procedure will have been sufficiently accurate. Cumulative exposure in the period following the end of men's exposure records was set equal to the final exposure. This approach was appropriate for men whose exposure records ended while the Attendance Records System was still operating at their collieries. For most of them, the end of the exposure record will have coincided with their dates of leaving the industry. On the other hand, for men still working at the time when the Attendance Records System ended (the late 1970s), the procedure will have caused underestimation of the latter part of their working-time exposures. This shortfall will not have biased

exposure–response relationships (except possibly in the analysis of leukaemia cases) since a lag of 10 years was applied to cumulative exposure in all analyses. The use of a two–year lag in the analysis of acute leukaemia meant, in effect, that the actual lag varied from two to a maximum of about 12 years.

The choice of a 10–year lag for exposure variables was to some extent arbitrary, there being few precedents for a study of miners involving such low exposures. Recent analyses of US uranium miners' lung cancer mortality have used lags of five and 10 years (Whittemore and McMillan, 1983; National Research Council, 1988). Limited analyses (person–years method only) using lags of 5, 15 and 20 years did not change the results in any important way. For analyses of mortality from leukaemia (excluding chronic lymphoid) a shorter lag was judged appropriate; Darby *et al* (1987), in a study of 14111 ankylosing spondylitis patients given a single course of X–ray treatment, reported that the excess death rate from leukaemia was greatest 2.5 to 4.9 years after treatment.

Smoking habit was also treated as a time–dependent variable in both types of statistical analysis. A similar approach to that used for exposure variables was adopted: interpolation gave estimates of smoking habit between surveys, and smoking category was assumed unchanged following the final PFR attendance. This assumption was of doubtful validity since results from miners who had attended a sequence of four PFR surveys suggested that tobacco consumption declined over the period. If this reflected the trend in smoking habit for the complete study group then, on average, men's smoking habit will have been overestimated during the later part of the study period.

A lag of five years was applied to smoking habit, in all analyses. This allowed for the possibility that men who later became lung cancer cases might have modified their smoking habit on experiencing the onset of symptoms.

5.5.2 Person-years analyses

Tables of death rates by factors of interest were used to analyse associations between radon and thoron daughter exposure and mortality from two causes - lung cancer and stomach cancer. Numbers of deaths from these causes were large enough to ensure that death rates had reasonable statistical stability. Direct inspection of exposure-response relationships, by tabular or graphical means, was carried out; such descriptive methods helped the interpretation of regression analyses.

Calculation of SMRs, using regional population statistics, was carried out only for all-cause mortality, and lung cancer. The purpose of these analyses was to establish the magnitude of the lung cancer death rate in the study group, and to compare it to that of the general population. However, variations in SMR with exposure category were not examined. Since the external population had an average level of exposure comparable to that of the study population, comparison with population rates would have offered no information concerning exposure effects beyond what would be obtained in analyses carried out entirely within the study group.

5.5.3 Case-referent studies

Case-referent studies were carried out for 10 of the 11 causes of death considered for this study. The corresponding method of statistical analysis (conditional logistic regression) used exposure estimates in their original form rather than the categorized versions used in person-years analysis; tests for trend might therefore be expected to have somewhat greater power as a result. Adjustment for the effects on death rates of age, smoking, colliery and calendar time was effected by matching cases to referents; for causes with small numbers of deaths, this method was preferred to the alternative of including confounding variables in regression models. Referents for lung cancer and stomach cancer cases were randomly sampled from strata defined by confounding variables. Case-referent ratios were chosen primarily to give data files which could be conveniently processed using available software. Thus, lung cancer cases were matched to four referents, and stomach cancer

cases to 10 referents. Data for 2390 and 1932 subjects respectively were obtained, to which conditional logistic regression models incorporating second order terms could be fitted reasonably quickly. Four referents per case was judged to be the minimum acceptable ratio; the width of confidence limits shown in the Table of Section 5.1.2 suggests that the loss of power in comparison to person-years analysis due to sampling has not been very great. Sampling was not used for other causes of death, since inclusion of all available referents did not produce unmanageably large datasets for analysis.

5.5.4 Use of 'colliery adjustment' in analysis

Relative risks reported in Chapter 4 were all 'colliery-adjusted' - that is, in person-years analyses, indicator terms for colliery were included in regression models; and in case-referent studies, cases and referents were matched on colliery. This option was preferred to the alternative of not adjusting for colliery, on the grounds that unadjusted associations might have been due, in part or entirely, to a relationship between lung cancer mortality and some unknown factor, whose colliery mean levels were positively associated with colliery mean radioactivity levels. (The possibility of such confounding was the main weakness of the preliminary correlation analysis which provided the impetus for the present study. Incidentally, a repeat of the preliminary analysis, using colliery-specific relative risks, adjusted for age, calendar time and smoking, showed non-significant Spearman rank correlations with colliery mean levels of radon and thoron daughters, after incorporation of the mortality data from PFR2 attenders.) A disadvantage of colliery adjustment is that it will have resulted in some loss of statistical power, since variation in exposure within collieries was, in general, less than that between (Figures 4.7 and 4.8). However, results of limited person-years analyses, with adjustment only for age, calendar time and smoking habit, suggested that the loss will not have been great. Thus, for radon daughters, the estimated relative risk per WLM was 1.03 (95% confidence limits 0.98 to 1.08); and for thoron daughters, 1.15 (95% confidence limits 1.00 to 1.31). Note that these confidence intervals are not substantially narrower than those shown in the Table of Section 5.1.2. Note also that this analysis shows an association between thoron daughter exposure and lung cancer; but since the apparent

relationship disappears after adjustment for colliery, it should not be regarded as supplanting the results of Chapter 4, which are summarized in Section 5.1.2.

5.5.5 Three co-exposures and their potential for counfounding

Allowing for colliery differences may not guard against possible biases induced by co-exposures with substantial within-colliery variation. Three such were diesel exhaust fume, mixed coalmine dust, and quartz.

In the late 1970s, it was reported that extracts from soot particles in diesel exhaust were mutagenic to bacteria. Since then, many cohort studies of diesel-exposed populations, and numerous case-control studies, mainly of lung and bladder cancer in relation to diesel exhaust exposure, have been carried out. Mauderly (1992) reviewed the epidemiological evidence, and concluded that 'long-term employment in jobs with susbstantial exposures to diesel exhaust is associated with a 20% to 50% increase in risk for lung cancer'.

Although few, if any, measurements of diesel exhaust particles are available from PFR data, measurements of concentrations of diesel exhaust fume within the cabins of so-called 'man-riders' are moderately numerous. These data, combined with information on travelling times, could provide estimates of cumulative exposure to diesel-exhaust fume, or, more likely, of a surrogate of exposure. In principle therefore, it would have been possible to control for the effects, if any, of diesel exhaust exposure in the present study. However, the task would have amounted to a major exposure assessment exercise, which could not have been carried out within the project's resources. In the event, it was judged reasonable to dispense with such adjustment, on the grounds that the influence of the confounder would very likely be weak, and that the magnitude of the adjustment would itself be subject to large uncertainty because of the difficulty of estimating the co-exposure. Incidentally, variation between men in diesel exposure is to some extent 'explained' by their colliery of employment, since diesel transport was not used at four of the 10 collieries. Thus, colliery adjustment will have provided a partial adjustment for the effect of diesel exposure. The

fact that radon daughter levels were lower at these four collieries (2.56 mWL compared to 6.98 mWL) shows that the potential for confounding does exist.

In a review of lung cancer mortality in British coalminers, Goldman (1965) concluded that low SMRs observed in coalminers could not be explained by differences in smoking habit, or by mining communities being located in areas of low atmospheric pollution. The possibility that exposure to coalmine dust might somehow protect against lung cancer was mentioned in discussion, and some supporting data cited. Were this speculation true, one would expect unadjusted estimates of relative risk due to radon and thoron daughter exposure to be biased downwards, because cumulative dust exposures, within colliery, would be positively correlated with radiation exposures. Since Goldman's article was published, a number of studies have been carried out, which provide relevant information.

The studies of Liddell (1973) and Cochrane *et al* (1979) have already been mentioned in Section 1.7. Briefly, Liddell estimated SMRs for working miners from death certificates, colliery information on employment, and results of a census of the coalmining industry. Lung cancer SMRs showed an increasing gradient, from 0.49 for Face Workers, through 0.53 for workers 'Elsewhere Underground', to 0.82 for Surface Workers, which might be interpreted as consistent with the notion that dust exposure is protective. However, a similar gradient was observed for most of the other causes of death considered by Liddell, including occupational pneumocoiosis. (A notable exception was 'other accidents', where the trend was reversed.) Liddell described the gradient in the 'All causes' SMR (0.81, 1.10, 1.79) as consistent with a tendency for less fit men to move away from Face Work. It may be that health related job changes also partly account for the trend in lung cancer SMR.

Cochrane *et al* (1979) calculated lung cancer SMRs by category of pneumoconiosis in a group of 6212 non-miners, ex-miners and miners, followed up for 20 years. The general level of lung cancer mortality was low, and there was no evidence that increasing radiological category was associated with decreasing lung cancer risk. SMRs were 0.66 for non-miners,

0.70 for men without CWP (miners and ex-miners), 0.68 for men with CWP, and 0.80 for men with PMF.

Ames *et al* (1983) reported results of a case-control study of lung cancer in relation to coalmine dust exposure and cigarette smoking. Three hundred and seventeen cases were selected from three US cohorts of coalminers established between 1959 and 1969, and from a database generated by a National Autopsy study of coalminers. Two sets of deceased controls were chosen: (i) men from the same cohort, or from within the Autopsy Study, who had died from causes other than cancer or an accident, matched one-to-one on age at death and date of birth; (ii) men, again from within the same cohort and excluding cancer deaths or accidental deaths, but additionally matched (two controls per case) on cigarette smoking. (Smoking habit and occupational history information had been obtained from questionnaires administered when the cohorts were established.) As a check against possible bias induced by use of deceased controls, analyses were also carried out using two series of living controls. Cases from the Autopsy Study were excluded from this check. Analysis of the one-to-one matched series (both deceased and living controls) showed no significant effect of years of underground mining, characterized as a dichotomy - less than 25 years, 25 years or more. Similarly, there was no significant effect in the two-to-one series, where smoking had been allowed for by matching. The odds ratio for 25 years or more of underground mining was 0.89 (95% limits 0.66 to 1.20) estimated using deceased controls; and 0.80 (95% limits 0.48 to 1.32) using living controls.

The study of Miller and Jacobsen (1985) was mentioned in Section 7.1. Using a proportional hazards model, survivorship of lung cancer mortality was estimated in subcohorts of a study group of approximately 25000 British coalminers, defined by age and cumulative exposure to dust at the start of a 22 to 26 year follow-up period. The authors stated '... the analysis with respect to estimates of dust exposure showed no pattern that could be interpreted as indicating either a protective or a potentiating effect of exposure to coalmine dust'. Analysis of survivorship among smokers by pneumoconiosis category over a shorter follow-up (by five years) suggested a possible negative trend (P = 0.12). But the authors did not interpret this as

indicating a protective effect of dust exposure for two reasons: uncertainty that death registration data accurately reflect true cause of death, and the above-mentioned lack of relationship between survivorship and dust exposure.

To summarize, two large prospective studies of British coalminers have not supported Goldman's speculation that dust exposure might protect against lung cancer. In the US, where the evidence for reduced lung cancer rates in coalminers is less strong, a case-control study which controlled for smoking also failed to find a protective effect. The decision not to adjust for dust exposure in the present study was based on the lack of convincing evidence of an association, positive or negative.

Regarding quartz exposure, evidence has accumulated from epidemiological studies of many occupational groups - miners and quarrymen, tunnel workers, foundrymen - both for and against the possibility of a causal link with lung cancer. McDonald (1989) reviewed the evidence from cohort and case-control studies. Of nine cohorts of mine and quarry workers, raised lung cancer SMRs (1.27 to 1.56) were found in four, only one of which was controlled for smoking. Four of the other five studies failed to show an association, and the other, though suggestive, was based on a small sample, described by McDonald as probably unrepresentative. Two of the four negative studies were large surveys of gold miners with reasonably high statistical power of detecting association. McDonald also referred to five cohort studies of men with silicosis, each of which showed an SMR of at least 2.00, but only one of which included adjustment for smoking. Comparisons in all but one of these studies were with the general population; in the single exception, a register of silica-exposed subjects was used. Difficulties of interpretation were emphasized by McDonald, to do with the possible unrepresentativeness of the cohorts vis-a-vis quartz-exposed workers in general. Finally, the choice of control group in two of four case-control studies referred to was questionable in the reviewer's opinion; and the other two studies gave opposing answers. McDonald's overall conclusion was that the available evidence was insufficient to establish a causal relationship between quartz exposure and lung cancer.

Agius (1992), in a brief article, presented evidence for and against an association. Of studies published since McDonald's review, three of cohorts of silicotics showed increased lung cancer rates by factors of at least two; a case–referent study of lung cancer found elevated risks in ceramic workers relative to non–exposed workers; and a cohort study of South African gold miners showed an exposure–response relationship. However, no associations were found in a proportionate mortality study of Vermont granite workers, a cohort study of Sardinian silicotics, and a case–control study of South African gold miners. (Matching of controls in the latter study was subsequently criticised by the authors themselves.) Agius drew attention to a major difficulty in reviewing the epidemiological evidence for or against the carcinogenicity of quartz, namely, judging to what extent confounding factors, chiefly tobacco smoke but also chemical compounds and radon exposure may have contributed to an observed association. He concluded that the available data did not provide consistent support of the notion that silica exposure causes lung cancer, but that there was evidence of the enhancement of the effect of potent carcinogens.

Throughout PFR, quartz concentrations were measured within occupational groups, but individual cumulative exposures have been calculated only for subgroups of men involved in special studies. Calculation of such exposures in the present study would therefore have required an additional exposure assessment, not on the scale required for diesel fume, but considerable nevertheless. The decision not to consider quartz exposure in analysis was thus taken partly on grounds of practical constraint, but also in the knowledge that evidence for the carcinogenicity of quartz in man is limited.

5.6 Conclusions and Recommendations for Further Work

5.6.1 Conclusions

i) The case–referent study of lung cancer showed a statistically significantly increased relative risk of mortality per WLM radon daughter exposure (lagged by 10 years) in smokers of 6–10 cigarettes per day; and raised relative risks, but not significantly so, in non–smokers and smokers of 1–5 cigarettes per

day. Relative risks in heavier smokers were less than unity. Similar patterns of risk were observed for lagged thoron daughter exposure, and a combined measure of dose, but differences between smoking categories were significant only for the latter. The result presents difficulties of interpretation, and may be a combination of a genuine exposure effect in non- and light smokers, together with a bias caused by health-related job changes.

Person-years analyses did not show any relationship between lung cancer death rates and either radon or thoron daughter exposure.

ii) There was an association between each of radon and thoron daughter exposure, and oesophageal cancer; which took the form of an increased risk for men in their fifties, which declined strongly with age. Overall, both associations were negative. The result may be due to a health-related selection effect, but this conjecture cannot be checked from PFR data.

iii) For none of the other causes of death examined (cancer of the stomach, oral cavity, larynx, bone, prostate, kidney; malignant melanoma, leukaemia [excluding chronic lymphoid]) was there evidence of an association between death rate and exposure to radon or thoron daughters.

iv) The upper limit of the 95% confidence interval for the relative risk per WLM radon daughter exposure was 1.064; the corresponding value for thoron was 1.258. These values may be interpreted as the maximum relative risks consistent with the data. An approximate analysis to gauge the effect of measurement errors in estimates of seam means, and of recall errors in estimates of time worked, raised these upper limits to 1.081 and 1.305 respectively.

5.6.2 Recommendations for further work

To dismiss the finding of a positive association between lung cancer mortality and radon daughter exposure in light smokers, because of the problematical negative association in heavy smokers, would be premature. More detailed

analysis of PFR data might clarify the finding. Specifically, the plausibility of the proposed selection mechanism could be investigated by examining job histories of cases and referents, to check if heavy smokers who eventually died from lung cancer tended to transfer to surface work more frequently than their surviving colleagues.

More generally, the present work could be usefully extended by undertaking a more detailed assessment of exposure, but confined to collieries where working time exposure made a sizeable contribution to total exposure, namely C, K, P, Q, T and Y. The use of ventilation distance as a 'predictor' appears especially appropriate at C and Q where single seams (essentially) were worked. Adoption of a case-referent design would keep numbers of subjects within bounds; thus a rough classification of domestic exposure might even be attempted, since men's addresses are held on PFR files. The gain would be an analysis of increased power, and hence a narrowing of confidence limits on risk estimates.

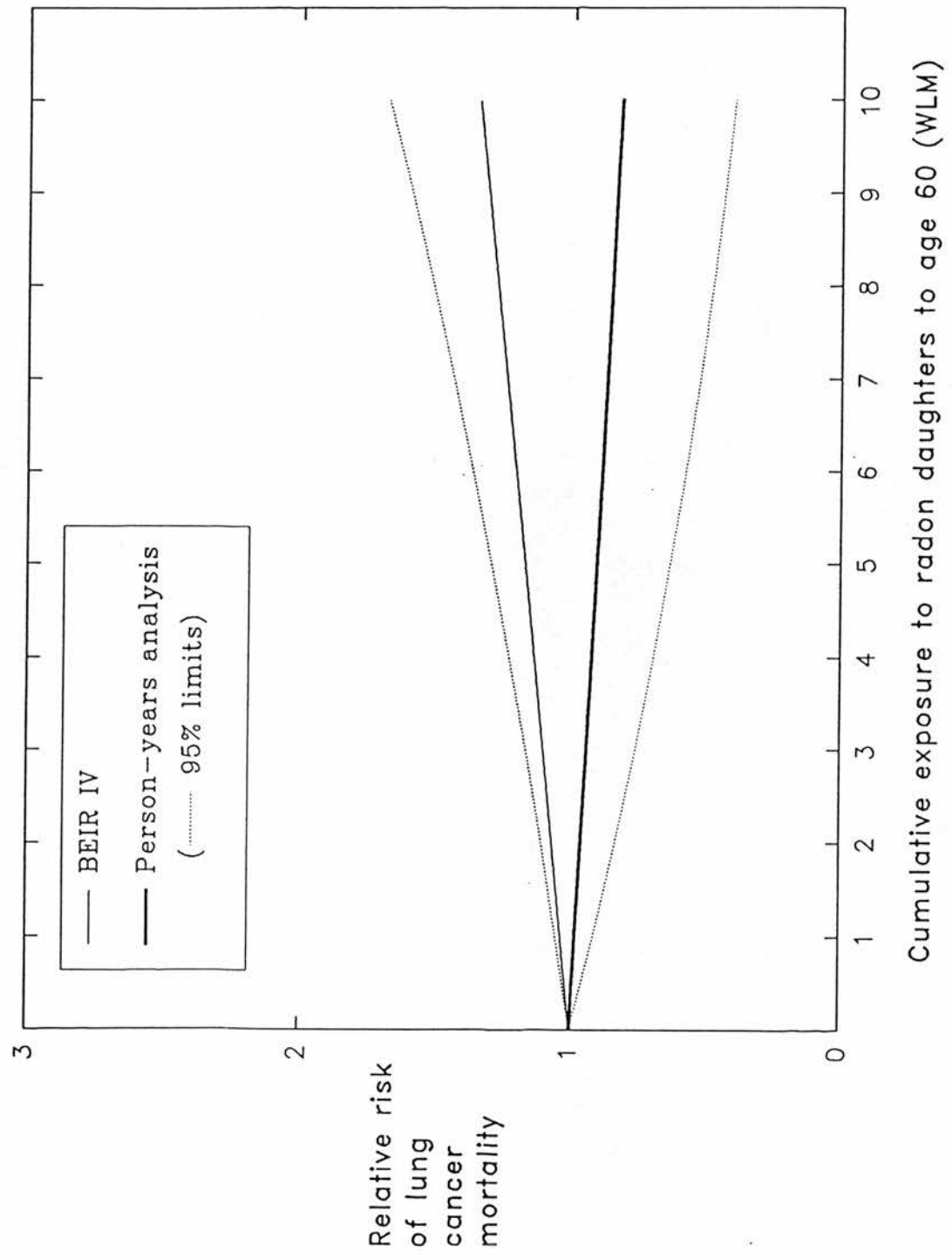

Figure 5.1: Relative risk of lung cancer mortality per WLM radon daughter exposure, estimated by person-years analysis, with 95% confidence limits; together with relative risk predicted by the BEIR IV Committee's Time Since Exposure model.

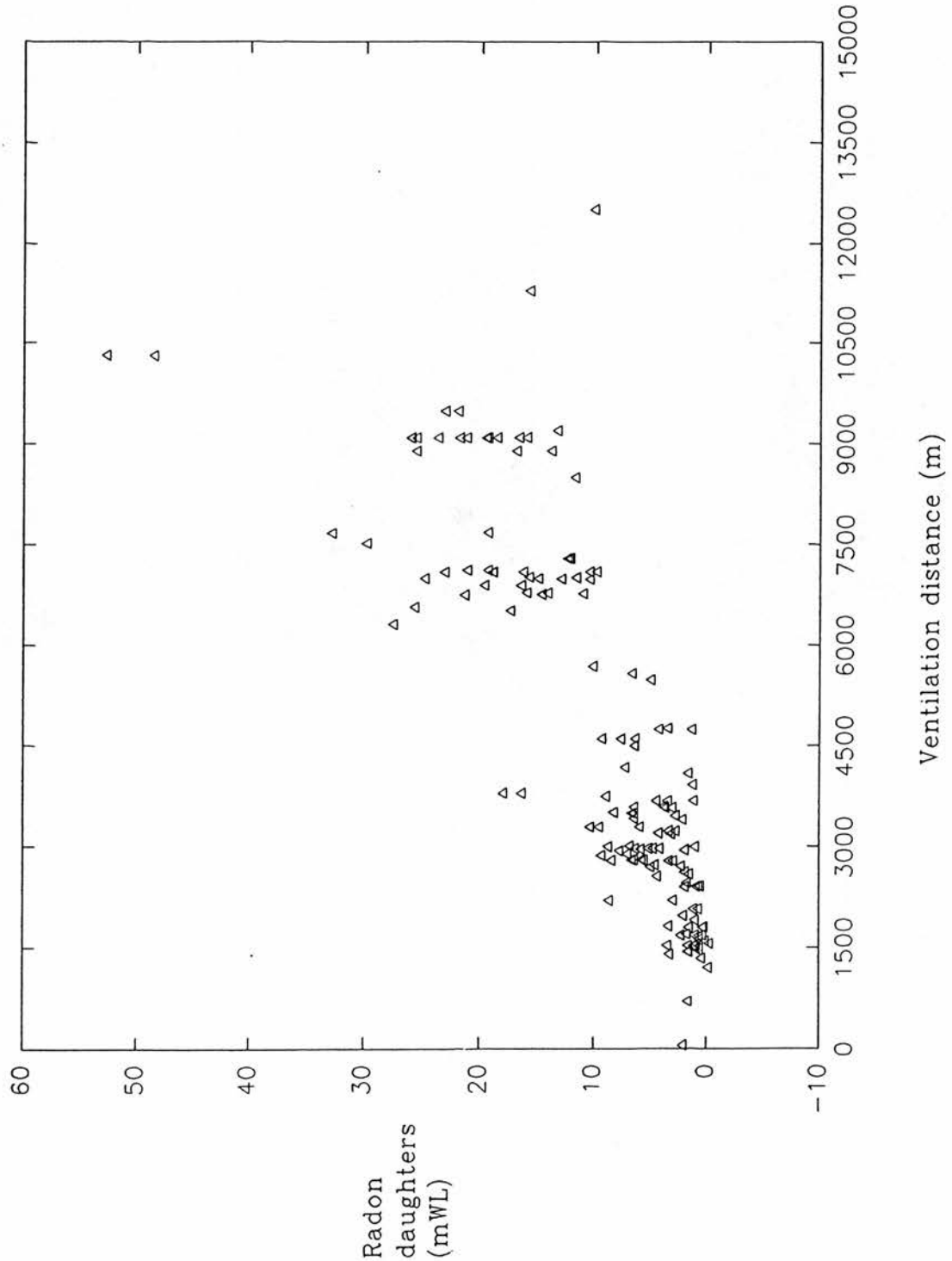

Figure 5.2: Scatter diagram, relating 157 measurements of radon daughters made at 11 collieries in the 1970s, to distance travelled by the ventilating airstream from pit bottom to point of measurement.

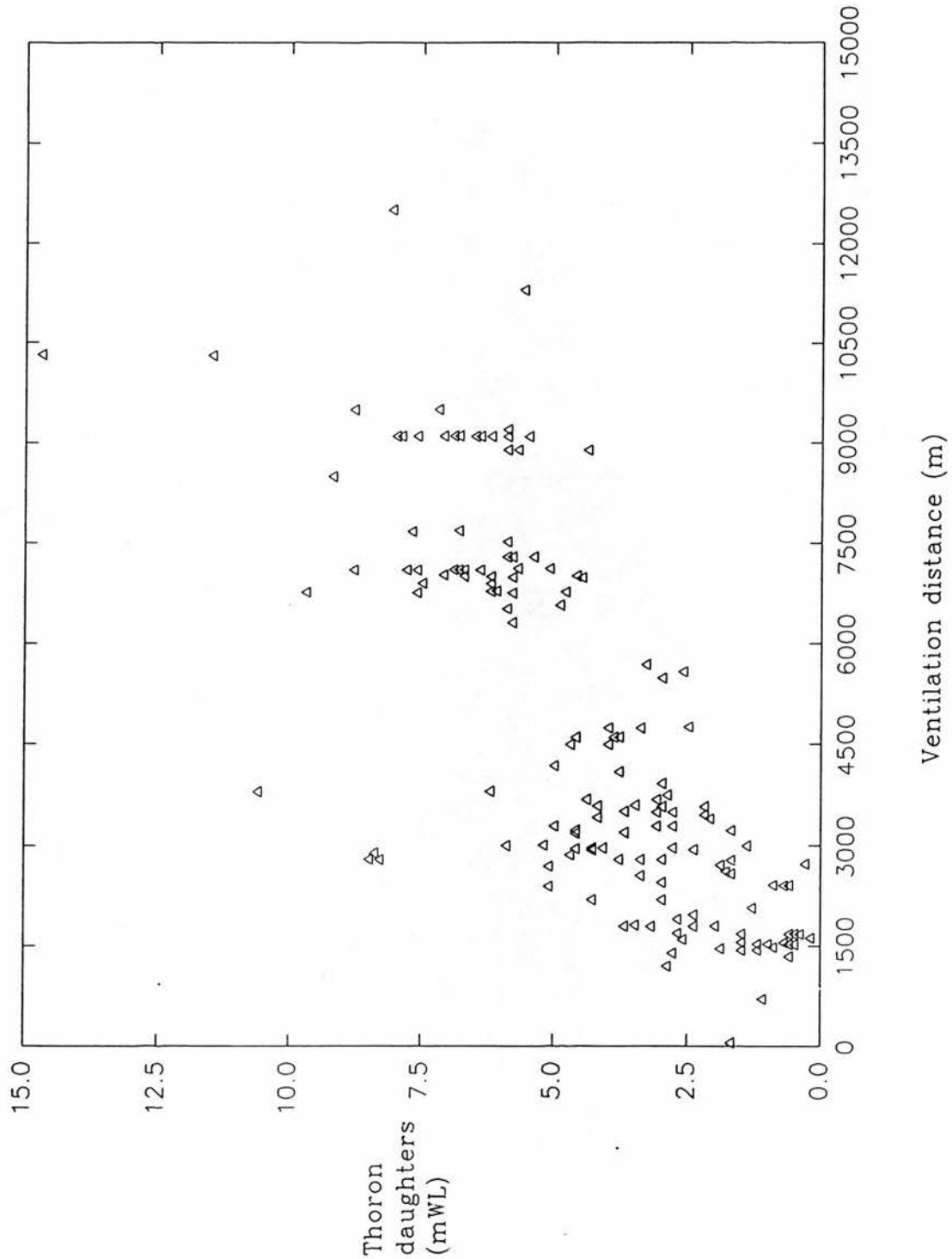

Figure 5.3 Scatter diagram, relating 157 measurements of thoron daughters made at 11 collieries in the 1970s, to distance travelled by the ventilating airstream from pit bottom to point of measurement.

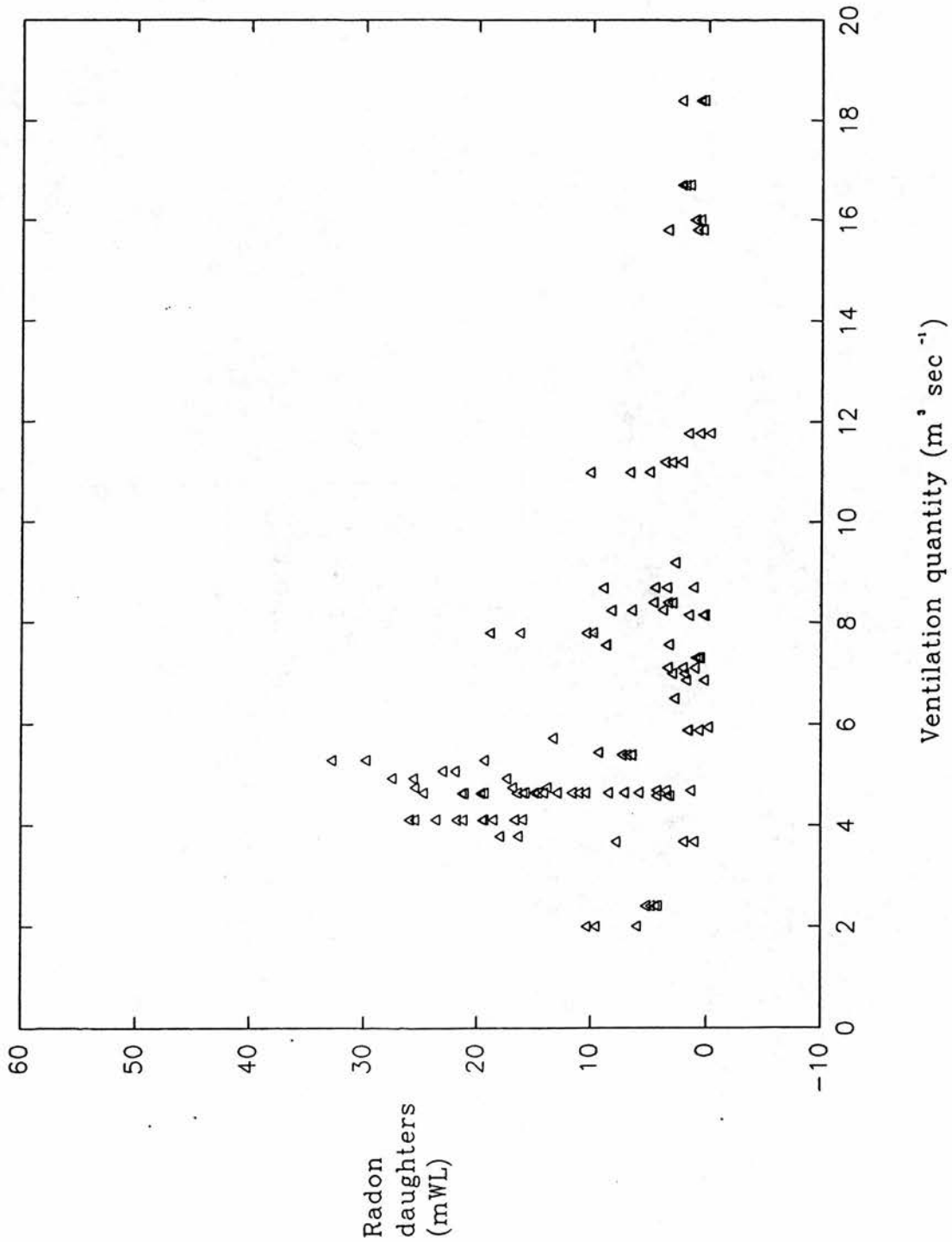

Figure 5.4 Scatter diagram, relating 128 measurements of radon daughters made at 10 PFR collieries in the 1970s, to ventilation quantity (i.e. volume of air passing measurement point per second).

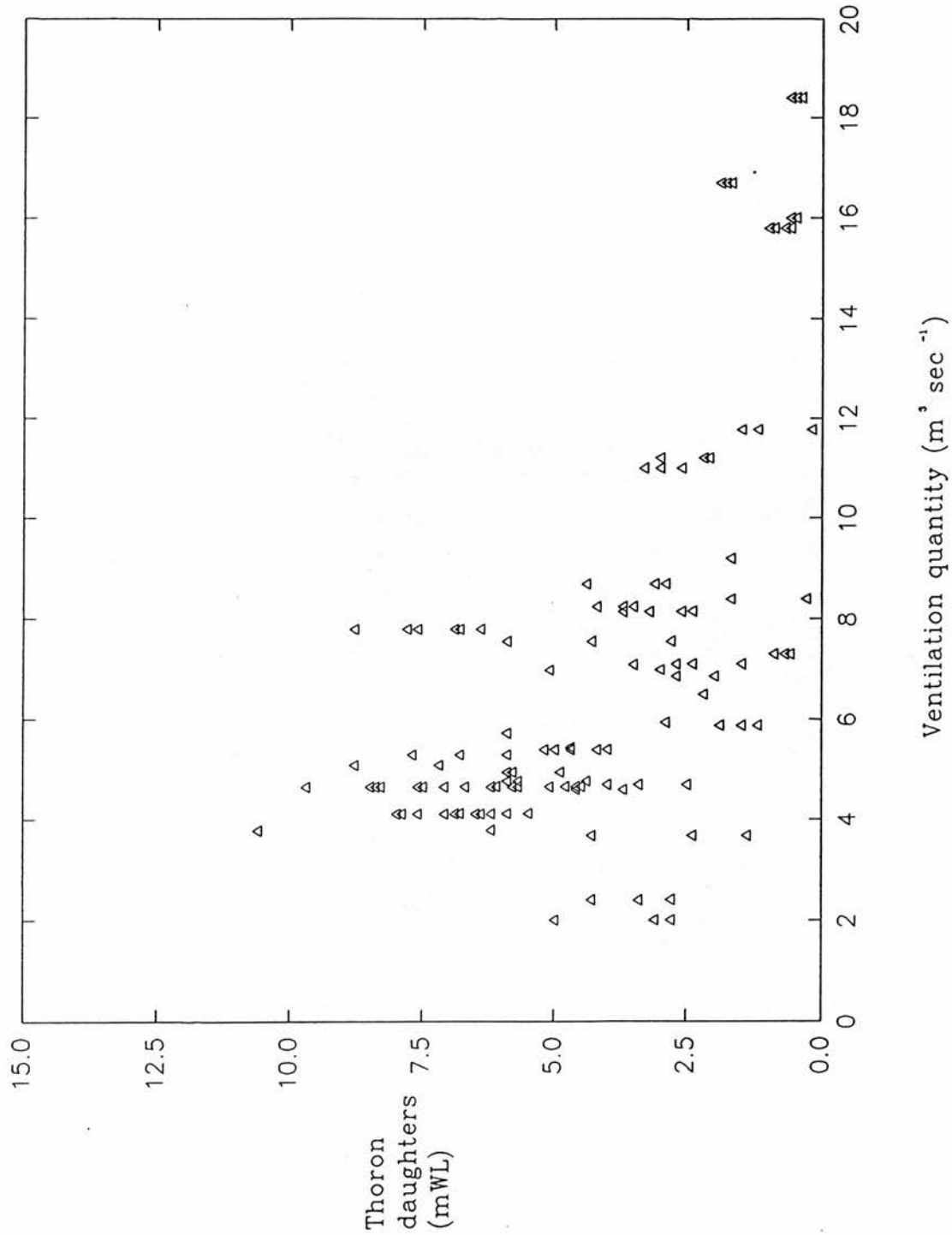

Figure 5.5 Scatter diagram, relating 128 measurements of thoron daughters made at 10 PFR collieries in the 1970s, to ventilation quantity (i.e. volume of air passing measurement point per second).

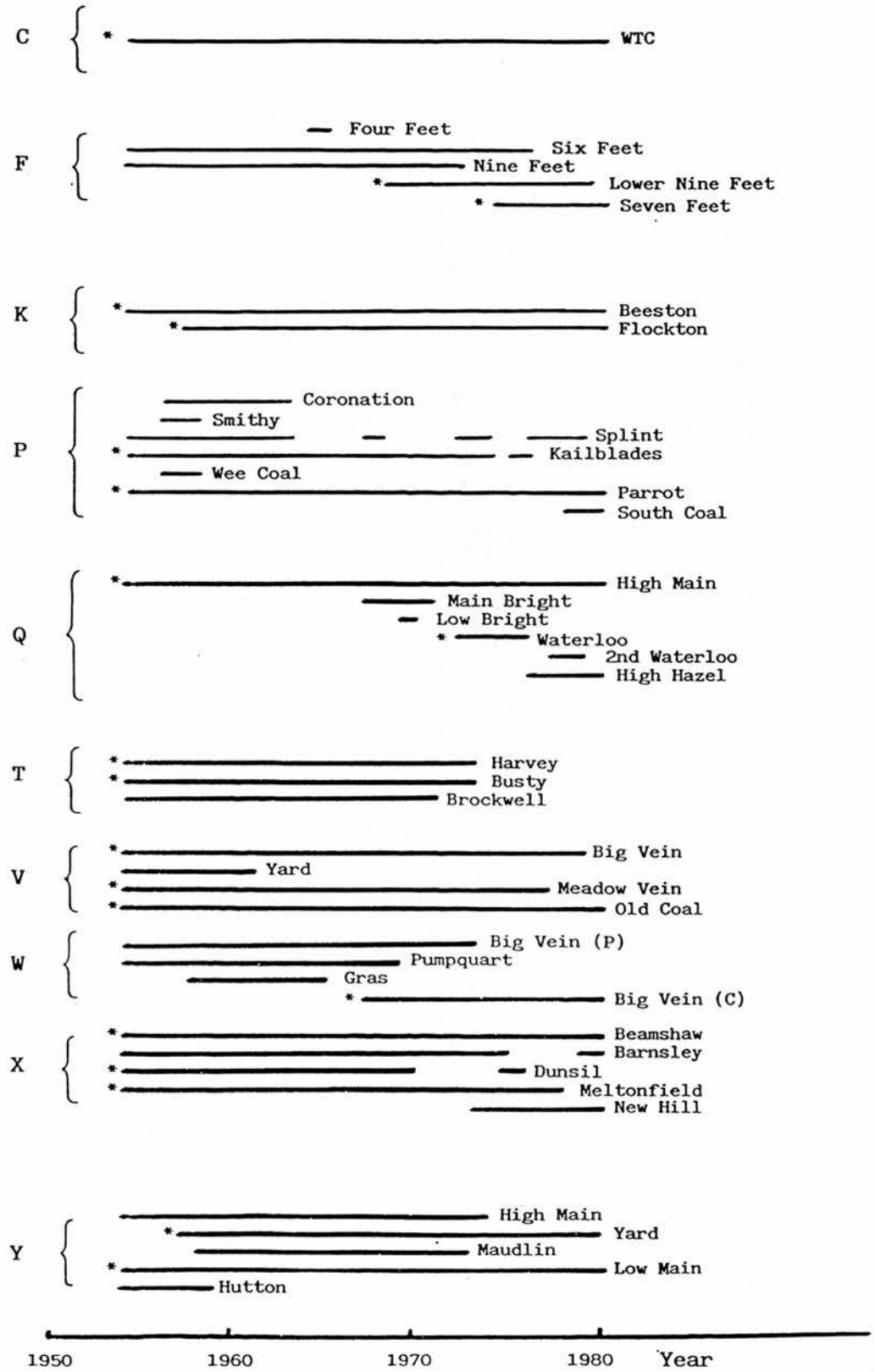

Figure 5.6 Working seams at 10 PFR collieries during the life of the Field Research. Seams where measurements were made during the 1970s are marked*.

Table 5.1 Analysis of variance of the natural logarithm† of radon daughter levels (mWL).

Source of variation	df	MS
Colliery	10	16.19***
+ Seam (within colliery)	11	1.09***
+ Ventilation distance (m)	1	3.18***
Residual	129	0.24
Total ‡	151	1.37

*** $P < 0.001$

† See footnote to Table 3.2.

‡ One measurement at colliery T had no ventilation distance recorded.

Table 5.2 Analysis of variance of the natural logarithm† of thoron daughter levels (mWL).

Source of variation	df	MS
Colliery	10	5.575***
+ Seam (within colliery)	11	0.290***
+ Ventilation distance (m)	1	0.702**
Residual	129	0.083
Total ‡	151	0.466

*** $P < 0.001$ ** $P < 0.01$

† See footnote to Table 3.3.

‡ See footnote to Table 5.1.

Table 5.3 Analysis of variance of the natural logarithm† of radon daughter levels (mWL).

Source of variation	df	MS
Colliery	9	15.93***
+ Seam (within colliery)	10	1.16***
+ Ventilation quantity (m^3 sec^{-1})	1	0.79
Residual	107	0.24
Total ‡	127	1.43

*** $P < 0.001$

† See footnote to Table 3.2.

‡ All nine underground measurements at colliery H could not be assigned ventilation quantities. The same applied to 16 non-face measurements at six PFR collieries.

Table 5.4 Analysis of variance of the natural logarithm† of thoron daughter levels (mWL).

Source of variation	df	MS
Colliery	9	5.534***
+ Seam (within colliery)	10	0.291***
+ Ventilation quantity (m^3 sec^{-1})	1	0.340*
Residual	107	0.084
Total ‡	127	0.489

*** $P < 0.001$ * $P < 0.05$

† See footnote to Table 3.3.

‡ See footnote to Table 5.3.

Table 5.5 Average proportion (%) of total time worked in eight categories, for the 12361 study group members.

Time worked category	Average proportion
Attendance records:	
Seams with measurements	16
Seams with no measurements	7
Underground work not specific to seams	14
Surface	11
Unclassifiable Occupational Groups	2
Occupational histories:	
Underground, research colliery	27
Underground, non-research colliery	15
Surface	8

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APPENDIX 1

Quantities of radioactivity and their units of measurement

Measured radon and thoron daughter levels which form the basis of the exposure variables analysed in this study, were recorded in units of milli-working levels (mWL). The working level (WL) is the traditional unit of energy concentration for decay products of radon and thoron.

One WL of radon daughters is present when the alpha energy per litre of air, released by decay to ^{210}Pb, is 1.3×10^5 MeV. The same definition holds for thoron daughters, except that decay is to ^{208}Pb. The radioactivity concentration of the daughters is measured by the equilibrium equivalent decay product concentration (denoted $EEDC_{222}$ for radon daughters, $EEDC_{220}$ for thoron daughters), in units of Becquerels per cubic metre (Bq m^{-3}). The EEDC is a weighted mean of the individual daughter activity concentrations: if each of the daughters had an activity concentration equal to the EEDC, the total alpha energy released would be equal to the energy concentration of the combination actually present. Conversion from energy concentration to EEDC is given by

1 WL = 3740 Bq m^{-3} (radon daughters);

1 WL = 276 Bq m^{-3} (thoron daughters),

(Nero, 1988).

The equilibrium factor is the ratio of the EEDC to the activity concentration of radon (or thoron) gas.

The units of cumulative exposure which were used in statistical analyses were working-level hours (WL hour). Thus, 1 hour worked in an energy concentration of 1 WL gives a cumulative exposure of 1 WL hour. However, relative risks were presented using the more usual working-level

month (1 WLM = 170 WL hour). This was to allow easier comparisons to published work.

APPENDIX 2

Table A2.1 Results of a survey of radon and thoron daughter levels carried out at 11 British collieries between 1972 and 1980.

Colliery (Sampling dates)	Seam*	Ventilation distance (m)	Ventilation quantity ($m^3\ sec^{-1}$)	Radiation levels (mWL)	
				Radon Daughters	Thoron Daughters
C	Warwickshire	2803	4.66	5.8	8.5
(Dec 1976-	Thick Coal	2796	4.66	8.5	8.3
Feb 1977)		2892	4.66	7.1	8.4
		1683	7.10	1.1	1.5
		1817	7.10	3.4	3.5
		1909	7.10	1.1	2.7
		1974	7.10	2.1	2.4
		2949	3.68	2.0	2.4
		2999	3.68	1.1	1.4
		2938	3.68	7.8	4.3
F	Seven Feet	1679	18.40	0.7	0.4
(Aug 1976-		1681	18.40	2.3	0.6
Sep 1976)		1683	18.40	0.4	0.5
		1524	16.00	1.1	0.5
		1523	16.00	0.7	0.6
		1532	16.00	1.2	0.6
	Lower Nine	2409	7.30	1.0	0.7
	Feet	2411	7.30	0.6	0.6
		2413	7.30	0.8	0.9
K	Beeston	5480	11.00	5.0	3.0
(Nov 1972-		5685	11.00	10.2	3.3
Dec 1972)		5575	11.00	6.7	2.6
		11300	-	15.8	5.6
	Flockton	3510	8.25	8.3	3.7
		3600	8.25	3.8	3.5
		3420	8.25	6.5	4.2
		8500	-	11.8	9.2

Table A2.1 Continued

Colliery (Sampling dates)	Seam*	Ventilation distance (m)	Ventilation quantity (m^3 sec^{-1})	Radiation levels (mWL)	
				Radon Daughters	Thoron Daughters
H	Busty	3500	-	6.5	2.8
(Nov 1977-		3500	-	6.7	3.1
Jan 1978)		3500	-	6.5	2.8
		2800	-	5.6	3.4
		2800	-	6.7	3.8
		2800	-	6.5	3.0
	Tilley	4600	-	6.4	4.6
		4600	-	7.7	3.8
		4600	-	9.4	3.9
	(Upcast shaft)	7300	-	12.2	5.9
		7300	-	12.5	5.8
		7300	-	12.3	5.4
	(Workshop, surface)	Not applicable		0.3	0.2
		Not applicable		0.4	0.2
		Not applicable		0.2	0.1
P	Kailblades	3231	4.60	3.4	4.6
(Apr 1976-		3200	4.60	4.3	3.7
May 1976)		3186	4.60	3.2	4.6
	Parrot	4755	4.70	3.5	2.5
		4741	4.70	4.3	4.0
		4737	4.70	1.4	3.4
		3685	8.70	4.5	4.4
		3682	8.70	1.2	3.1
		3682	8.70	3.5	3.1
Q	High Main	8900	4.77	16.9	5.7
(Apr 1972-		8900	4.77	13.9	5.9
Nov 1972)		8900	4.77	25.6	4.4
		9100	4.12	18.6	6.2
		9100	4.12	23.7	6.4
		9100	4.12	21.9	7.9
		9100	4.12	19.4	7.6
		9100	4.12	21.3	6.8
		9100	4.12	26.0	7.1
		9100	4.12	26.1	8.0
		9100	4.12	16.0	6.9
		9100	4.12	16.7	5.9
		9100	4.12	19.6	6.5

Table A2.1 Continued

Colliery (Sampling dates)	Seam*	Ventilation distance (m)	Ventilation quantity ($m^3\ sec^{-1}$)	Radiation levels (mWL)	
				Radon Daughters	Thoron Daughters
Q	High Main	9100	4.12	25.6	5.5
(Apr 1972-		7100	7.80	9.9	7.8
Nov 1972)		7100	7.80	10.5	6.8
		7100	7.80	19.0	8.8
		7100	7.80	18.9	6.9
		7100	7.80	19.0	6.4
		7100	7.80	16.3	7.6
		7100	-	23.1	6.7
		9500	5.09	23.1	7.2
		9500	5.09	22.0	8.8
		3800	3.79	16.4	10.6
		3800	3.79	18.0	6.2
		9200	5.73	13.4	5.9
(Jun 1979-		7525	5.30	29.9	5.9
Jul 1979)		7685	5.30	19.4	6.8
		7675	5.30	32.9	7.7
		6310	4.95	27.6	5.8
		6517	4.95	17.4	5.9
		6572	4.95	25.7	4.9
(Apr 1980-		6988	4.66	10.5	4.5
Jun 1980)		6756	4.66	21.4	5.8
		6994	4.66	13.0	5.8
		6762	4.66	14.7	7.6
		7000	4.66	15.0	6.2
		6768	4.66	14.7	9.7
		7006	4.66	24.8	6.7
		6774	4.66	11.1	4.8
		7012	4.66	11.7	4.6
		6783	4.66	14.2	6.2
		7021	4.66	15.8	7.1
		6789	4.66	16.0	6.1
		10314	-	52.8	11.5
		10314	-	48.6	14.7
		7126	4.66	19.4	5.7
		6897	4.66	16.5	6.2
		7129	4.66	21.2	5.1
		6902	4.66	19.7	7.5
(Apr 1972-	Waterloo	1400	7.56	3.3	2.8
Nov 1972)		2200	7.56	8.7	4.3
		3000	7.56	8.8	5.9

Table A2.1 Continued

Colliery (Sampling dates)	Seam*	Ventilation distance (m)	Ventilation quantity (m^3 sec^{-1})	Radiation levels (mWL)	
				Radon Daughters	Thoron Daughters
Q (Apr 1972- Nov 1972)	(Pit bottom, air from High Main and Waterloo)	50	-	2.1	1.7
		12500	-	10.2	8.1
T (Jan 1973- Feb 1973)	Busty	3292	2.00	10.4	3.1
		3292	2.00	9.6	5.0
		3292	2.00	6.0	2.8
	Harvey	2560	2.40	4.4	3.4
		2972	2.40	5.2	2.8
		2972	2.40	4.8	2.8
		2972	2.40	4.2	4.3
	(Pit bottom, air from Harvey)	-	-	7.1	3.8
V (Oct 1973- Mar 1974)	Old Coal	2730	8.40	4.6	0.3
		2790	8.40	3.0	1.7
		2790	8.40	3.4	1.7
		1440	5.88	1.7	1.2
		1440	5.88	1.6	1.5
		1460	5.88	0.7	1.9
		1480	15.80	1.0	0.9
		1340	15.80	0.5	0.6
		1530	15.80	3.5	1.0
		1550	15.80	0.9	0.7
		700	-	1.7	1.1
	Big Vein	3580	11.20	3.1	3.0
		3580	11.20	3.7	2.2
		3400	11.20	2.2	2.1
	Meadow Vein	1530	11.77	1.7	1.2
		1620	11.77	0.7	0.2
		1560	11.77	-0.2	1.5
W (Apr 1974)	Big Vein	2590	16.70	1.6	1.7
		2710	16.70	2.3	1.9
		2620	16.70	2.0	1.8
		2072	-	0.8	1.3
		2072	-	0.8	1.3
		2072	-	1.2	1.3

Table A2.1 Continued

Colliery (Sampling dates)	Seam*	Ventilation distance (m)	Ventilation quantity ($m^3\ sec^{-1}$)	Radiation levels (mWL)	
				Radon Daughters	Thoron Daughters
X	Meltonfield	1200	5.94	-0.1	2.9
(Feb 1976)		1700	6.86	1.8	2.7
		1800	6.86	0.3	2.0
	Dunsil	1600	8.15	0.2	2.6
		1800	8.15	0.4	2.4
		1800	8.15	0.3	3.2
		1800	8.15	1.6	3.7
	Beamshaw	2200	6.99	3.0	3.0
		2400	6.99	2.0	5.1
Y	Yard	2970	-	6.4	4.1
(Apr 1978-		2960	-	5.9	4.6
Feb 1979)		2700	-	5.0	5.1
		2460	-	1.8	3.0
		4090	-	1.7	3.8
		3920	-	1.3	3.0
		3590	5.40	6.5	4.2
		4495	5.40	6.5	4.7
		4495	5.40	6.4	4.0
		4180	5.40	7.3	5.0
		3010	5.40	6.9	5.2
		3460	6.50	2.8	2.2
		2870	5.45	9.4	4.7
	Low Main	3750	8.70	9.0	2.9
		3230	9.20	2.8	1.7

* Locations not specific to a seam appear in brackets.

APPENDIX 3

This Appendix gives the 'PANDA' questionnaire on respiratory symptoms and smoking used at routine PFR surveys.

Series 700

Form B.991

INSTITUTE OF OCCUPATIONAL MEDICINE

PNEUMOCONIOSIS FIELD RESEARCH

INSTRUCTIONS FOR PANDA 11

A PERSONAL DATA

Date of birth — **Month**: January – December = 01 – 12. Enter code for the month with leading zero for January – September

Year: Enter the last two digits of the year (i.e. tens and units)

B RESPIRATORY SYMPTOMS QUESTIONNAIRE

Q1, 2, 3 and 4: If YES enter 'Y', if NO enter 'N'

Q1a, 2a, 3a and 4a: If answer to previous question is NO then leave blank, otherwise enter 'Y' for YES and 'N' for NO

Q5, 6 and 7: If YES enter 'Y', if NO enter 'N'

Q8: If YES enter 'Y' and ask Qs. 8a – 8d, leaving Q8e blank
If NO enter 'N' and ask Q8e, leaving Qs. 8a – 8d blank

- **Q8a**: Enter 'C' for Cigarettes only
  'P' for Pipe only
  'B' for Cigarettes and Pipe
- **Q8b and 8c**: Enter number of cigarettes with leading zero if less than 10 or '00' if none
- **Q8d**: Enter 'X' for ½ ounce only, otherwise enter the number of ounces or '0' for none
- **Q8e**: Enter 'Y' for YES and 'N' for NO

Q9: Enter 'Y' for YES and 'N' for NO

- **Q9a**: If answer to Q9 is NO leave blank, otherwise enter
  'A' for Asthma
  'B' for Bronchitis
  'C' for Cold
  'D' for Bronchitis and Asthma
  'F' for Influenza
  'S' for some other chest illness
  'X' for chest injury (not regarded as chest illness). Do not amend answer to Q9

C & D ANTHROPOMETRIC DATA AND VENTILATORY FUNCTION

Enter leading zeros where appropriate

ADDITIONAL QUESTIONING

If difficulty is experienced in obtaining 'YES' or 'NO' apply the following:
"I know this is difficult but please try to answer 'YES' or 'NO'
I will repeat the question"
If the answer is again equivocal, record 'NO'

APU 2089

PANDA 11

COLLIERY LETTER [ ] 1

A PERSONAL DATA

NAME ..... X-RAY NUMBER 2 [ ][ ][ ][ ] 5

DATE OF BIRTH (MONTH & YEAR) 6 [ ][ ][ ][ ] 9

B RESPIRATORY SYMPTOMS QUESTIONNAIRE

PREAMBLE: "I am going to ask you some questions about your chest - about cough and spit, for example. Please try to answer 'Yes' or 'No'. Your answers will be treated confidentially.

COUGH

Q. 1	Do you cough when you get up or first thing in the morning?	10
Q.1a	Do you cough like this on most days for as much as 3 months in the year?	11
Q. 2	Do you cough during the rest of the day? - I don't mean just at the end of your shift.	12
Q.2a	Do you cough like this on most days for as much as 3 months in the year?	13

PHLEGM

Q. 3	Do you bring up phlegm when you get up or first thing in the morning?...	14
Q.3a	Do you bring up phlegm like this on most days for as much as 3 months in the year?	15
Q. 4	Do you bring up phlegm during the rest of the day? - I don't mean just at the end of your shift. ...	16
Q.4a	Do you bring up phlegm like this on most days for as much as 3 months in the year?	17

BREATHLESSNESS

Q. 5	Do you have to walk slower than other people on level ground because of your chest?...	18

WHEEZING

Q. 6	Do you ever have wheezing or whistling in your chest? - I don't mean only when you have a cold. ...	19

WEATHER

Q. 7	Does the weather affect your chest?	20

SMOKING

Q. 8	Do you smoke? (If 'Yes', Q.8a – 8d; If 'No', Q.8e)	21
Q.8a	Do you smoke cigarettes, a pipe or both? (Record C, P or B)	22
Q.8b	How many cigarettes do you smoke per day on Mondays to Fridays? 23	24
Q.8c	How many cigarettes do you smoke per day on Saturdays and Sundays? 25	26
Q.8d	How many ounces of tobacco do you smoke per week? (Record in ounces. x = ½)...	27
Q.8e	Have you ever smoked as much as one cigarette per day for one year?	28

CHEST ILLNESSES

Q. 9	In the last 3 years have you had a chest illness that has kept you off work for more than a week?...	29
Q.9a	If 'Yes', what did your doctor say it was?	30

(A = Asthma; B = Bronchitis; C = Cold; D = Bronchitis & Asthma; F = Influenza; S = Some other chest illness; X = Not a chest illness)

C ANTHROPOMETRIC DATA

Height (cms)	31 [ ][ ][ ]	33
Sitting Height (cms)	34 [ ][ ][ ]	36
Weight (kgms)	37 [ ][ ][ ]	39

D VENTILATORY FUNCTION

Second Blow	F.E.V.	40 [ ][ ][ ]	42
	F.V.C.	43 [ ][ ][ ]	45
Third Blow	F.E.V.	46 [ ][ ][ ]	48
	F.V.C.	49 [ ][ ][ ]	51
Fourth Blow	F.E.V.	52 [ ][ ][ ]	54
	F.V.C.	55 [ ][ ][ ]	57

APPENDIX 4

Smoking Habit – Derivation of Codes

For convenience, items 8 to 8e of the respiratory symptoms questionnaire administered from PFR2 onwards, and given in full as Appendix 3, are reproduced here:

Respiratory symptoms questionnaire – items on smoking habit

8 Do you smoke? (If Yes, 8a–8d; If No, 8e.)

8a Do you smoke cigarettes, a pipe or both?

8b How many cigarettes do you smoke per day on Mondays to Fridays?

8c How many cigarettes do you smoke per day on Saturdays and Sundays?

8d How many ounces of tobacco do you smoke per week?

8e Have you ever smoked as much as one cigarette per day for one year?

When questionnaire responses obtained at PFR2 and 3 were computerized during the 1970s, there was some summarization of data. Items 8 and 8e were combined to form a new item, '88e', which had three codes – 0 (Non–smoker: 8 = No and 8e = No), 1 (Ex–smoker: 8 = No and 8e = Yes), and 3 (Smoker: 8 = Yes). Items 8b and 8c on numbers of cigarettes smoked per day were also combined to form '8b8c'), by taking a weighted mean of weekday and week–end consumption. The result was computerized in the following form:

Cigarettes per day	Code (item 8b8c)
0	0
1-5	1
6-10	2
11-20	3
21-30	4
31-40	5
41-50	6
51-	7

Item 8d, on pipe tobacco consumption was coded thus:

Ounces per week	Code (item 8d)
0	0
½	1
1	2
2	3
3	4
4	5
5	6
>5	7

Data obtained during Phase 2 were not summarized before computerization.

As stated in the main report, men's smoking habits at each PFR survey at which they provided valid data were coded according to the following scheme:

Smoking habit	Code
Non-smoker	1
Ex-smoker	2
Pipe smoker	3

Cigarette, or cigarette and pipe smoker:

Equivalent of 1 to 5 cigarettes per day	4
" " 6 to 10 " " "	5
" " 11 to 20 " " "	6
" " 21 to 30 " " "	7
" " 31 to 40 " " "	8
" " over 41 " " "	9

The key to codes 1, 2 and 3 is given in the following table:

Code	Questionnaire responses	
	PFR 2 or 3	PFR4 onwards
1	88e = 0	8 = 'No', 8e = 'No'
2	88e = 1	8 = 'No', 8e = 'Yes'
3	88e = 3, 8b8c = 0,8d>0	8 = 'Yes', 8a = 'Pipe'

Codes 4 to 9 were used for men who smoked cigarettes, or cigarettes and pipes; i.e. men for whom combined items 88e and 8b8c equalled 3, and exceeded zero, respectively (PFR2 and 3); or for whom item 8 equalled 'Yes' and item 8a equalled 'cigarettes' or 'both' (PFR4 onwards).

The tobacco consumption of these men was expressed in units of equivalent cigarettes per day, one ounce of pipe tobacco per week being taken as equivalent to 5 cigarettes per day. Numbers of cigarettes smoked, or ounces of pipe tobacco, were not available at PFR2 or 3 other than in the coded forms discussed above; estimated amounts were therefore taken as the mid-points of ranges, with 55.5 cigarettes per day, and 6 ounces of pipe tobacco per week being used for the highest rates of consumption. With these assumptions, tobacco consumption ('Equivalent cigarettes') reported at PFR2 or 3 was calculated as:

$$\text{Equivalent cigarettes} = \text{cigarettes per day} + 5 \times \text{ounces of pipe tobacco per week.}$$

Data from later surveys had not been summarized before computerization; tobacco consumption was calculated as:

$$\text{Equivalent cigarettes} = {}^{5}/_{7} \times \text{cigarettes per week-day} + {}^{2}/_{7} \times \text{cigarettes per week-end day} + 5 \times \text{ounces of pipe tobacco per week.}$$

APPENDIX 5

Tables of Person-years and numbers of deaths

Tables A5.1 and A5.2 give data on which Figures 4.9 to 4.16 are based. The slight discrepancy between the tables in the person-years total is due to rounding error. Tables A5.3 and A5.4 are by calendar time period x smoking habit and colliery, respectively.

Table A5.1 Total person-years at risk (PY), lung cancer deaths (LC) and stomach cancer deaths (SC), by age at risk and cumulative exposure to radon daughters, lagged by 10 years.

Age at risk		Cumulative exposure to radon daughters (10-year lag) (WL hour)							
		0-	25-	50-	100-	200-	400-	800-	All
⩽ 34	PY	8263	2335	2203	1001	609	-	-	14411
	LC	0	0	0	0	0	-	-	0
	SC	0	0	0	0	0	-	-	0
35-44	PY	11208	7793	7249	7016	2853	1921	1	38041
	LC	0	1	2	2	0	0	0	5
	SC	0	0	0	1	0	0	0	1
45-54	PY	7515	11417	13673	12601	9846	3750	1272	60075
	LC	3	8	9	6	14	3	1	44
	SC	4	2	3	2	3	3	0	17
55-64	PY	2957	8126	14747	12832	16646	6307	3291	64906
	LC	9	20	38	36	34	10	5	152
	SC	2	9	12	13	12	6	4	58
65-74	PY	1090	4030	8618	7326	11482	7386	2700	42632
	LC	6	20	36	32	65	33	15	207
	SC	0	9	15	18	33	11	2	88
⩾ 75	PY	223	999	2480	1862	3293	2219	843	11919
	LC	0	6	15	14	27	28	8	98
	SC	0	4	4	4	11	12	2	37
All	PY	31256	34700	48970	42639	44729	21584	8106	231983
	LC	18	55	100	90	140	74	29	506
	SC	6	24	34	38	59	32	8	201

Table A5.2 Total person-years at risk (PY), lung cancer deaths (LC) and stomach cancer deaths (SC), by age at risk and cumulative exposure to thoron daughters, lagged by 10 years.

Age at risk		Cumulative exposure to thoron daughters (10-year lag) (WL hour)						
		0-	25-	50-	100-	200-	400-	All
⩽ 34	PY	8358	4034	1874	145	-	-	14411
	LC	0	0	0	0	-	-	0
	SC	0	0	0	0	-	-	0
35-44	PY	11057	7431	12582	6481	490	-	38041
	LC	0	2	3	0	0	-	5
	SC	0	0	1	0	0	-	1
45-54	PY	10466	7984	14797	21999	4828	1	60075
	LC	6	4	11	17	6	0	44
	SC	4	4	2	4	3	0	17
55-64	PY	6517	7123	12087	19391	18585	1203	64905
	LC	18	18	31	41	44	0	152
	SC	8	5	9	17	17	2	58
65-74	PY	2203	5569	5371	8077	19389	2023	42632
	LC	14	20	15	48	96	14	207
	SC	3	9	11	16	48	1	88
⩾ 75	PY	427	1581	1258	1917	5970	766	11919
	LC	0	10	8	15	58	7	98
	SC	0	6	3	5	20	3	37
All	PY	39028	33722	47969	58009	49261	3993	231982
	LC	38	54	68	121	204	21	506
	SC	15	24	26	42	88	6	201

Table A5.3 Total person-years at risk, lung cancer deaths and stomach cancer deaths, by calendar time period and smoking habit.

Smoking habit		Calendar time period			
		1960-69	1970-79	1980-89	All
Non-	PY	6909	13248	11263	31420
	LC	1	2	0	3
	SC	6	8	13	27
Ex-	PY	3989	12064	12600	28653
	LC	1	13	19	33
	SC	5	9	14	28
Pipe	PY	3460	6419	4742	14621
	LC	3	12	16	31
	SC	0	9	8	17
Cigarettes:					
1-10	PY	12280	20534	13511	46325
	LC	11	51	47	109
	SC	9	18	15	42
11-20	PY	19369	35699	24750	79818
	LC	27	79	110	216
	SC	13	36	14	63
21-	PY	7644	12708	10792	31144
	LC	11	51	52	114
	SC	2	11	11	24
All	PY	53652	100672	77658	231982
	LC	54	208	244	506
	SC	35	91	75	201

Table A5.4 Total person-years at risk, lung cancer deaths and stomach cancer deaths, by colliery.

Colliery	Person-years	Number of deaths	
		Lung cancer	Stomach cancer
C	24679	78	33
F	15224	27	17
K	20302	39	18
P	23796	41	14
Q	25111	52	17
T	24033	71	23
V	34298	55	30
W	12210	15	6
X	24620	53	21
Y	27709	75	22

APPENDIX 6

Person-years analysis of lung cancer mortality at colliery Q

Lung cancer death rates showed no evidence of increasing trends with radon daughter exposure, within age groups (Table A6.1). An analysis of deviance, treating exposure as a continuous variable, and allowing for age, smoking habit and calendar time, did not show a statistically significant effect of exposure (Table A6.2); the estimated relative risk was 0.96 per WLM radon daughter exposure.

There was also no evidence of any relationship between thoron daughter exposure and death rates (Table A6.3). Analysis of deviance gave a chi-squared statistic of 0.16 on 1 df, and the estimated relative risk was 0.94 per WLM thoron daughter exposure.

Likelihood ratio tests of interaction with stratifying variables were likewise not statistically significant, although there was a suggestion ($P<0.1$) that the relationship with thoron daughter exposure varied with smoking category (Table A6.4). Relative risks per WLM showed a similar pattern of variation as emerged in the case-referent studies:

	Radon daughters	Thoron daughters
Non-smokers	No deaths	No deaths
Ex-smokers	0.90	0.79
Pipe smokers	2.08	1.58
Cigarette smokers: 1-10	1.20	2.18
11-20	0.92	0.81
21-	0.83	0.56

Analysis using logged exposures gave very similar results. Main effects of exposure were both negative and did not approach statistical significance. Tests of interaction also gave non-significant results (Table A6.5); as in the case of the untransformed exposure, the interaction between thoron daughter

exposure and smoking habit approached significance ($0.05<P<0.1$). Relative risks per doubling of exposure showed a pattern similar to that found in the analysis of untransformed exposure:

	Radon daughters	Thoron daughters
Non-smokers	No deaths	No deaths
Ex-smokers	0.94	0.94
Pipe smokers	22.63	1.94
Cigarette smokers: 1-10	1.76	2.16
11-20	0.94	0.93
21-	0.76	0.68

The high estimate of relative risk per doubling of radon daughter exposure in pipe smokers is due to the fact that the two men who died were both in the highest exposure category.

Table A6.1 Lung cancer death rate per 100000 person-years, numbers of observed lung cancer deaths, and person-years at risk, by age at risk and lagged radon daughter exposure, for men at colliery Q.

Age at risk		Radon daughter exposure (WL hour)						
		0-	25-	50-	100-	200-	400-	800-
45-54	rate	285	430	0	0	319	95	79
	obs	1	1	0	0	3	3	1
	PY	351	233	300	414	939	3151	1272
55-64	rate	0	0	0	472	0	242	152
	obs	0	0	0	1	0	4	5
	PY	250	352	193	212	370	1650	3251
65-74	rate	830	432	0	1291	1556	419	556
	obs	1	1	0	1	2	2	15
	PY	121	232	93	77	129	477	2700
75-	rate	0	3183	0	0	0	1884	949
	obs	0	2	0	0	0	1	8
	PY	9	63	20	13	18	53	843

Table A6.2 Analysis of deviance of lung cancer death rate, in relation to radon daughter exposure at colliery Q.

Factor	df	Deviance
Age (A)	5	68.07***
+ Smoking habit	5	18.17**
+ Calendar time (T)	2	3.47
+ A.T	9	11.98
+ Radon	1	0.45
Residual	517	107.48
Total	539	209.62

** $P<0.01$
*** $P<0.001$

Table A6.3 Lung cancer death rate per 100000 person-years, numbers of observed lung cancer deaths, and person-years at risk, by age at risk and lagged thoron daughter exposure, for men at colliery Q.

Age at risk		Thoron daughter exposure (WL hour)					
		0	25-	50-	100-	200-	400-
45-54	rate	303	0	458	0	122	0
	obs	2	0	3	0	4	0
	PY	659	390	655	1678	3276	1
55-64	rate	0	0	409	0	289	0
	obs	0	0	1	0	9	0
	PY	578	308	244	867	3118	1203
65-74	rate	1064	342	0	1323	193	702
	obs	2	1	0	3	2	14
	PY	188	292	90	227	1036	1995
75-	rate	0	2454	0	5263	1073	866
	obs	0	2	0	1	2	6
	PY	11	81	28	19	186	692

Table A6.4 Likelihood ratio tests of interaction between stratifying variables and the two exposure variables, radon and thoron daughters.

Stratifying variable	df	Chi square	
		Radon daughters	Thoron daughters
Age	5	1.97	3.14
Calendar time	2	1.02	0.23
Smoking habit	5	7.44	9.29†

† $0.05<P<0.1$

Table A6.5 Likelihood ratio test of interaction between stratifying variables and the logarithmic transform of the two exposure variables, radon and thoron daughters.

Stratifying variable	df	Chi square	
		Radon daughters	Thoron daughters
Age	5	2.69	3.72
Calendar time	2	0.10	0.11
Smoking habit	5	7.89	9.30†

† $0.05<P<0.1$